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Distributed Problem Solving: Adaptive Networks with a Computer Intermediary Resource

Part One: Group Problem-Solving Performance in a Simulated Military Situation Assessment Task Under Varying Environmental Conditions

Part Two: Group Acquisition of Dynamic Control Skills in a Fluid Level Adjustment Problem

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Networking of information sources in relation to an organizing center is often a requirement for finding solutions to problems that individuals cannot solve alone. The process may require ongoing situation assessment by the problem-solving participants and the sharing of assessment progress via transfer of information over physically restricted communication links. The communication process may occur under conditions in which the participants are stressed. In the experiment reported in this Research Note, three, physically separated Macintosh computer workstations were placed in mutual communication under various restrictions and monitored by a fourth computer that served as a file server and central data collection resource. The problem was presented as animated tanks moving across a master battlefield terrain map with different, overlapping, limited portions of the map shown on the screen at each workstation. With various restrictions placed on the communication channels, subjects sent and received messages and tried to arrive at conclusions regarding tank action parameters. Twenty-four college students participated as subjects.
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DISTRIBUTED PROBLEM SOLVING: ADAPTIVE NETWORKS WITH A COMPUTER INTERMEDIATE RESOURCE. PART ONE: GROUP PROBLEM-SOLVING PERFORMANCE IN A SIMULATED MILITARY SITUATION ASSESSMENT TASK UNDER VARYING ENVIRONMENTAL CONDITIONS. PART TWO: GROUP ACQUISITION OF DYNAMIC CONTROL SKILLS IN A FLUID LEVEL ADJUSTMENT PROBLEM

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Part One

GROUP PROBLEM SOLVING PERFORMANCE IN A SIMULATED MILITARY SITUATION ASSESSMENT TASK UNDER VARYING ENVIRONMENTAL CONDITIONS

Abstract

Networking of information sources in relation to a an organizing center is often a requirement for approaching solutions to real world problems that no lone human can solve. Part of the process may require ongoing situation assessment by the problem solving participants and the sharing of assessment progress via transfer of information over physically restricted communication links. Often, the communication process may occur under conditions where the participants may be personally stressed in various ways. In the experiment reported here, three, physical partition separated, Macintosh computer workstations were placed in mutual communication under various restrictions and monitored by a fourth computer that served as a file server and central data collection resource. The problem situation was presented as antimated tanks moving across a master battlefield terrain map with different, overlapping, limited, portions of the map shown on the screen at each workstation. With various restrictions placed on the communication channels, subjects sent and received messages and tried to arrive at conclusions regarding tank action parameters. Twenty-four college students participated as subjects. A 10% and a 50% probability of detection of the observer by the "enemy" produced a threat situation and certain operational consequences if detection occurred. The objective was to arrive at an estimate of enemy strength, destination, tactical objective, and observer location. The results suggest that a broadly accessible communications system produces higher quality situation assessment results but has certain constraints and caveats.

1.0 INTRODUCTION

In order to generate a viable solution for many real world problems, a broad spectrum of information is usually required—a spectrum that exceeds the range and capabilities of a lone human problem solver or a single source of information. When such a situation exists, the basic processes for problem solving, such as effective option generation and situation assessment, may require substantial broadening of database and problem solving resources. Namely, a number of experts with different, yet necessary resources are required to solve the problem. Each of the experts involved with the problem will presumably have differing areas of knowledge or expertise, and this is significant in that the experts must communicate and cooperate with each other in the sense that not one of them alone has the sufficient resources to solve the entire problem; mutual sharing of information is necessary to allow the group as a whole to produce a solution. Therefore, in a distributed problem solving situation the knowledge, expertise, and information needed for dealing with the problem will be found distributed among several experts. Furthermore, for the problem to be properly dealt with, the experts must work together as a team. This is the distributed problem solving concept, and using humans and appropriate support equipment can be an effective method for accessing such a broadened database and generating a viable solution. How humans interact with each other while using computers as intermediary resources for distributed problem solving tasks, however, remains open to many research questions.

The concept of team effort is one of the most important aspects of distributed problem solving. A team can be defined as a group of two or more people who are working towards a common goal/objective/mission, where each person has been assigned specific roles or functions to perform, and where completion of the objective requires some form of dependency among the group members (Dyer, 1984). Without a successful team effort, a distributed problem solving task cannot be dealt with in an efficient and effective manner.

Many real world problems fit into the distributed problem solving realm. In general, situation assessment, disaster management, medical diagnosis, business management, product research and development, operation of complex systems, and C^2/C^3I (command, control/command, control, communication, intelligence) environments all lend themselves to the distributed problem solving process. In each of these situations, a number of human experts function as a team to achieve some desired objective, using computers and appropriate support equipment to assist them in performing their work.

With growth in microprocessor technology, network technology, and the general complexity of many types of problems, it has been argued that problem solving tasks in certain distributed problem solving situations should be entirely automated. This argument is further bolstered by the vast amount of empirical psychological data showing both the limitations of human information processing capabilities and the effects of environmental pressures on these capabilities (e.g., Wickens, 1984; Jacobs, 1984; National Research

Council, 1982; Dawes, 1979; Shroeder & Benbasat, 1975; Dawes & Corrigan, 1974; Wright, 1974; Folkins, 1970; Nomikos et al., 1968; Monat et al., 1972; Hayes, 1964). For example, Hutchins et al. (1984) studied human performance in a military command and control (C^2) environment during a simulated air defense operation and found that in high-density situations operators were highly productive but decidely suboptimal in their performance. That is, in a situation where operators were overloaded, their performance was highly productive as measured by the number of missles they launched, while on the other hand, their performance was significantly suboptimal (e.g. use of poorer decision making strategies as the situation grew more complex) as measured by other indices.

Given the limitations in human information processing capabilities, many researchers have suggested the development of automated systems to contend with the distributed problem solving process. Lesser and Corkill (1981) propose a general architecture for an automated distributed processing system to deal with distributed interpretation, distributed network traffic-light control, and distributed planning. In Lesser and Corkill's approach, computerized nodes cooperatively problem-solve by exchanging partial tentative results (at various levels of abstraction) within the context of common goals. Wesson et al. (1981) and Ben-Bassat and Freedy (1982) propose that situation assessment tasks involved with military applications can and should be fully automated by using a distributed sensor network. These authors put forth a general architecture for an expert system and its associated sensor network that would perform problem solving tasks in a distributed situation assessment setting. In other papers, protocols for control, communication, and cooperation between expert system sensor nodes in a distributed problem solving network have been described (Smith & Davis, 1981; Yang et al., 1985).

Testbed systems and models have been developed for initial studies of automated distributed problem solving networks in detecting and tracking low flying aircraft (Lacoss & Walton, 1978), speech understanding (Erman et al., 1980), situation assessment (Wesson et al. 1981), vehicle monitoring (Lesser et al., 1982), and supervisory control (Govindaraj et al., 1985). Research such as this is aiming for an artificial intelligence (AI) system capable of distributed problem solving.

In the initial development of their AI testbeds, however, it is disturbing to note that a number of researchers have attempted to remove the central focus of any problem solving situation—the human element. Statler (1984), for example, has observed in the design and development phases of many complex human-machine systems that many engineers either ignore or do not understand the fundamental requirements of human sensory, cognitive, and physical characteristics and limitations; that is, they do not take into account the true needs and attributes of the potential human user population. Not all problem solving tasks in a distributed problem solving situation can be automated. In fact, it is not feasible at this time, nor even in the near future, to totally automate the human out of a complex problem solving situation such as disaster management or command/control environments. Different levels of human performance (sensory, cognitive and physical) can be vastly improved with automated assistance, however, automation cannot satisfactorily replace human capabilities entirely. Andriole and Haplin (1986) have stressed the important role of humans in the command/control process by stating that unless research and development attention is focused on the human element in the C^2 process, then it will not matter how sophisticated the automated systems are. This statement can be generalized to many other types of systems. Advantages and disadvantages of automation in both complex human-machine systems and problem solving situations have received much attention in human factors engineering studies (for example, see Edwards, 1977; Wiener & Curry, 1980; National Research Council, 1982; Mitchell, 1982; Boehm-Davis et al., 1983; Lederer, 1983; Melvin, 1983; Wiener, 1983; Wickens, 1984; Helander, 1985; Price, 1985; Kearsley & Seidel, 1985; Weiner, 1985; Parsons, 1985; Sheridan, 1986; Kantowitz & Sorkin, 1986, Czaja, 1986; Davis & Wacker, 1986).

While the efforts to automate some aspects of a distributed problem solving task appear to be a promising direction for research and development, many of the requirements in these problem situations will remain heavily dependent upon human skills. Flexible, creative thinking and the ability to reason inductively are important facets of distributed problem solving, and at this point in time, there is no computer capable of performing these functions. Therefore, humans will remain the central figure in the problem solving process. Rouse and Morris (1986) point out that while automation can result in the improvement of task performance and productivity, in addition to increasing organizational control, automated systems can also give rise to many types of unanticipated risks and problems. For instance, excessive downtime for repairs and calibrations occur with automated systems.

An illustrative example of unanticipated problems with AI systems was provided by TRW's "adept work station project" (Technical Survey, 1986). TRW explored the use of AI in battlefield situation assessment (SA) under AWSP. In attempting to make AI solve practical SA problems, the researchers at TRW were forced to re-examine some of the traditional beliefs associated with the AI field. One traditional belief, that of machines can reason by themselves, was rejected by TRW. The researchers found that AI offers no more reasoning capabilitiy than conventional computer algorithms, and that humans are required when reasoning is required, particularly for unexpected events. The human skills of improvising and using flexible procedures allow the human to handle unexpected events while the computer is quite incapable of doing so.

TRW's AWSP also showed the information processing problems that human operators can encounter when using an AI SA system. One of the systems that was being developed under AWSP was called the Battlefield Exploitation and Target Acquisition (BETA) system, a computerized situation assessor. It was a prototype designed to collect a variety of battlefield information, put it together, and display it to intelligence analysts. Initial experiments with BETA showed that analysts could quickly become overwhelmed with data, and a later experiment using army officers obtained similar results. In another experiment with army officers, the officers had complete control over the amount of information they received from BETA. At first, the officers relied on intuition and no data, and lost the battle. On the second run, they received all the data the system could deliver, became overloaded, and lost the battle. In between these two extremes lies the ideal amount of data, however, this amount can vary with individuals.

To overcome this human information processing overload, AI researchers attempted to develop machine reasoning and flexible software technology. This technology was implemented into AWSP, and BETA was to be capable of analyzing intelligence data on Soviet second-echelon forces, thereby decieasing the cognitive demands placed on the analysts. Unfortunately, BETA did not meet its objectives and was limited to deciding when Soviet vehicles would leave the road. Furthermore, the system had a limited knowledge base that was difficult to modify, and the interface between soldier and machine was slow and clumsy.

With the present, state-of-the-art AI technology, SA will remain a human-based task, as with many other distributed problem solving tasks. Although many of today's AI and expert system programs are impressive in a number of ways, they are not yet ready to take on critical tasks alone. Lehner (1986) has reviewed the application of AI techniques to computer-based support of command and control decision making and has concluded that these military expert systems operate only as intelligent interfaces rather than stand alone systems. In the foreseeable future, such programs will be used to assist human problem solvers in dealing with difficult and complex tasks. Projects such as TRW's AWSP are making important findings which are being applied to experimental computer systems that can aid the analysts in an SA task. As of now, the ability of the computer to function as an SA analyst in itself is very limited, and thus SA will be heavily dependent on human skills for the time being. However, as a diagnostic tool and data enhancer/processor, the computer has significant values as an SA aid. There is no doubt that computer and electronic techonology will by playing very major roles in tomorrow's battlefield by assisting commanders and soldiers in gathering, categorizing, analyzing, and distributing important C^3 data.

From this brief discussion, it is clear that the role of the human in a distributed problem solving task is secured. Since the technological trend is pushing towards implementing more automation and computer assistance, the need to understand and enhance user performance, user interaction, and user acceptance of computer technology is imperative. Furthermore, having knowledge of human-system performance characteristics in distributed problem solving situations can significantly enhance future management of such problems. The overall objective of this study was to identify and characterize some of the human problem solving behaviors that emerge when a computer intermediary resource is made an integral part of a distributed problem solving situation.

There were two specific purposes of this study. First, to study human communication in both stressed and unstressed situations, and second, to examine how different group communication protocols influence situation assessment performance.

A simulated battlefield situation assessment task was chosen as the distributed problem solving task. This was done for a number of reasons. First, battlefield situation assessment requires more than one person to carry out the required tasks. The SA group is a team, i.e. all members have a common objective—to assess the overall battlefield situation. Second, SA groups are often decentralized, and information processing and decisionmaking are distributed (Cohen et al., 1985). Third, a battlefield situation assessment environment can impose some severe environmental constraints that can affect the performance of the SA group. Some real world environmental constraints such as time limits, chances of enemy detection, and battlefield complexity can be implemented into the computer-simulated battlefield scenarios. Finally, this study was supported by the U. S. Army Research Institute under Contract MDA903-84-C-0355 with the UCLA Man-Machine-Environmental Engineering Laboratory, and it seemed appropriate to employ a distributed situation assessment task that was directly related to army matters.

2.0 EXPERIMENT

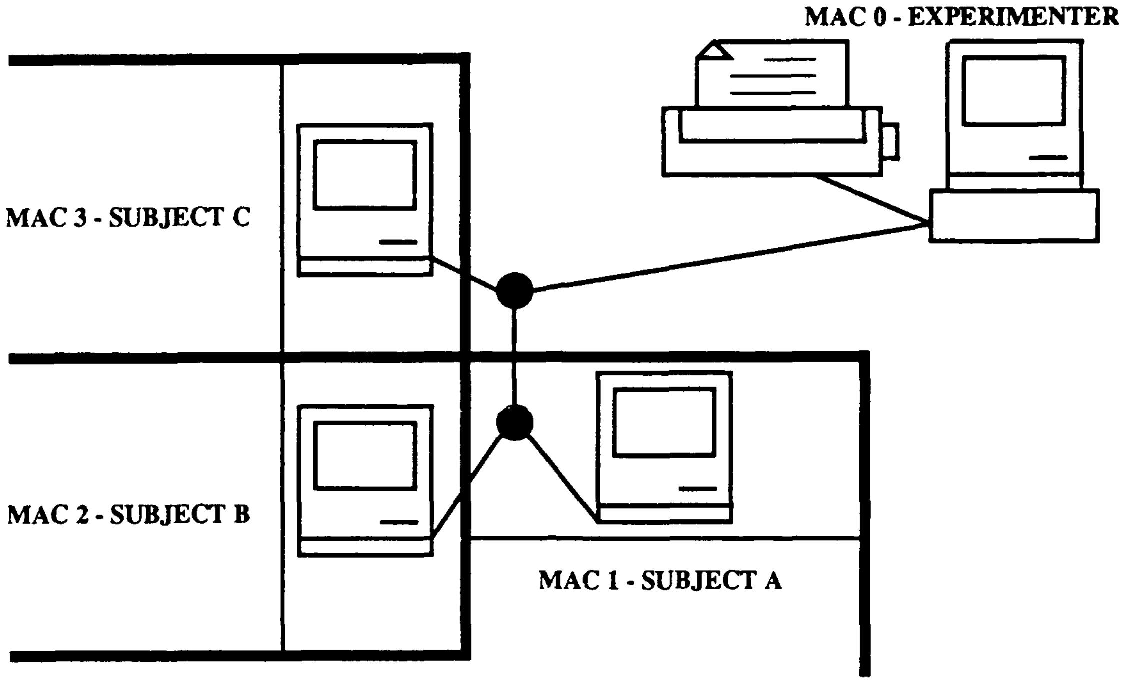
2.1 Method

2.1.1 Overview. This distributed situation assessment experiment was designed to study group problem solving behavior in a simulated, dynamic battlefield situation assessment task while using the computer as an intermediary resource. Specifically, this research examined how specific group communication protocols employed under different environmental conditions influenced distributed situation assessment performance.

The general experimental environment consisted of three, partition-separated human subject workstations, each containing a computer that was mutually networked according to specific experimental protocols. A fourth computer workstation functioned as the experimenter's workstation. The experimenter's computer system provided a mutually accessible file server, data management and data collection resource. For these studies, Apple Macintosh Plus computers were used, giving versatile capabilities for employing dynamic graphics, i.e. animated displays and maps, for studying distributed situation assessment performance. Subjects in a group saw different parts of a battlefield and had to formulate an overall picture of what was going on in the entire battlefield. Each subject received only a subset of the total set of information needed to assess the entire scenario. Solution to the assessment problem required each subject to organize and integrate their information subset with additional information received through communication with other subjects. Subjects interfaced with the problem situation and interacted with the other subjects through their respective computer systems.

2.1.2 Subjects. Twenty-four undergraduates (16 males and 8 females) at the University of California, Los Angeles participated in this study for course credit on a voluntary sign-up basis. For each experimental run, subjects were arranged into groups of three, thus making a total of eight groups. The subjects' ages ranged from 18 to 25 years. Most had little or no experience with Macintosh computers.

2.1.3 Materials and apparatus. A computer-controlled distributed situation assessment environment was developed using one Apple Macintosh Plus computer coupled to an 80 megabyte hard drive and the Pascal programming language to drive three other Macintosh Plus computers in separated, partitioned workstations. The main Macintosh was the experimenter's computer and was designated MAC 0. The other three Macintoshes were designated MAC 1, MAC 2, and MAC 3. MACs 1-3 were assigned to subjects A-C, repsectively. Figure 1 displays the Macintosh workstation layout. All four computers were



4 Macintosh computers, Imagewriter II printer, and Apple Talk network

Figure 1. Macintosh Workstation Layout

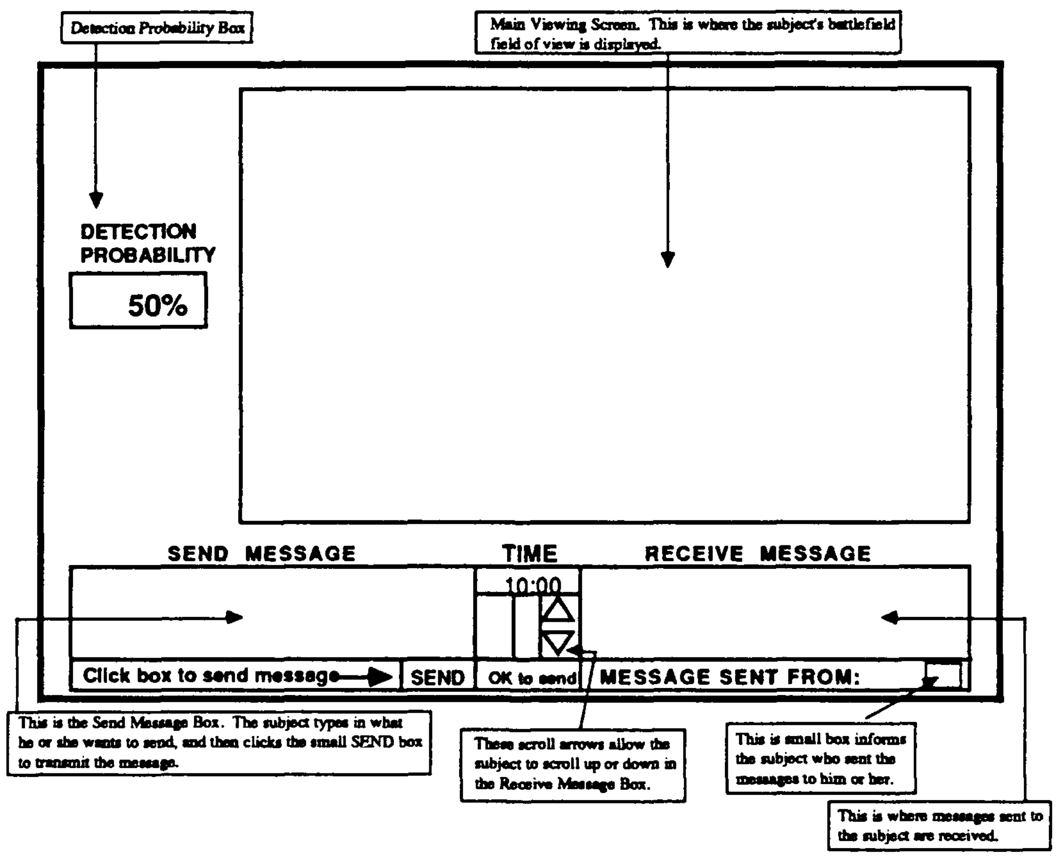


Figure 2. General Layout of Subjects's Macintosh Screen

connected with the Appletalk network.

Each Macintosh computer screen contained information on time allotted for situation assessment, probability of detection by the "enemy" (MAC 0), messages being sent and received, and an animated battlefield display. Figure 2 illustrates the screen that subjects see on their Macintosh computers.

2.1.4 Design. A between-subjects design was used. There were three between-subjects independent variables: communication protocols, probability of detection of a group's message transmission by MAC 0, and scenario complexity.

The first experimental variable was communication protocol. The subject population was randomly divided into two different communication protocol modes: **Broadcast Default Communication** (BRODCOM) and **Selective Default Communication** (SELCOM). Common to both communication protocol modes is the general method in which subjects interacted with each other. In order to communicate with one another, subjects had to use the keyboard to type in the message and the mouse pointing device to direct the message to the other subjects. For the BRODCOM group, the communication protocol was as follows. First, when a subject sent a message, it went to the other two subjects simultaneously; that is, anytime a subject sent a message, the other two subjects in the group automatically received it. For a subject to communicate with his or her group in the SELCOM mode, he or she had to select which of the other two subjects to transmit a message to. A subject in a SELCOM group only received a message that was sent specifically to him or her by another subject at a particular time. In both BRODCOM and SELCOM groups, subjects could chose to remain autonomous, i.e. to remain silent and not communicate with anyone in the group if the situation demanded it.

The experimental groups were randomly assigned to two different levels of **detection probability**. In this age of high technology warfare, electronic warfare (EW), electronic countermeasures (ECM), and electronic counter countermeasures (ECCM) play a very significant role in the battlefield. To add a simple case of EW to this study, and also to induce some sort of environmental constraint, probablity of detection was implemented into the computer system.

For a single message transmission, there were two levels of detection: 10% and 50%. What these probabilities meant was that each time a subject transmitted a message, there was x probability that the "enemy" (the experimenter's computer) would detect the transmission. The probability of detection was straight forward. Depending upon which detection level was used, each time a message was transmitted there was either a 10% or 50% chance of enemy detection. For example, if the 10% detection probability level was used, each time a message was transmitted there was a 10% chance that the "enemy" detected this transmission. The "enemy" (MAC 0) made these detections through a random number generation process. The consequences of a detection are explained in the procedure section. Subjects in both BRODCOM and SELCOM groups were informed of these probability differences. With respect to this independent variable, the three subjects in a situation assessment group had to weigh tradeoffs between the need for information and the probability of being detected by the enemy.

The third independent variable was **battlefield scenario complexity**. There were three levels of complexity—low, medium, and high. Scenario complexity was defined as the number of elements in the battlefield. Elements consisted of enemy (Red Force) tanks and type of battlefield terrain. The low-level complexity scenario was used as a demonstration and practice scenario for the subjects, while the medium- and high-level complexity scenarios were used for the actual experimental runs. Figures 3, 4, and 5 show the maps of the battlefields used for each scenario. The three types of scenarios will be described in a later section.

Three dependent variables were used to measure the effects of communication protocols on situation assessment performance: 1) accuracy of situation assessment, 2) subjective workload ratings of the situation assessment task, and 3) the degree of agreement between group members on their assessments of the battlefield situation.

Situation assessment performance was the measure of the **accuracy** of a particular group's overall assessment of the situation. Subjects' assessments were to contain the

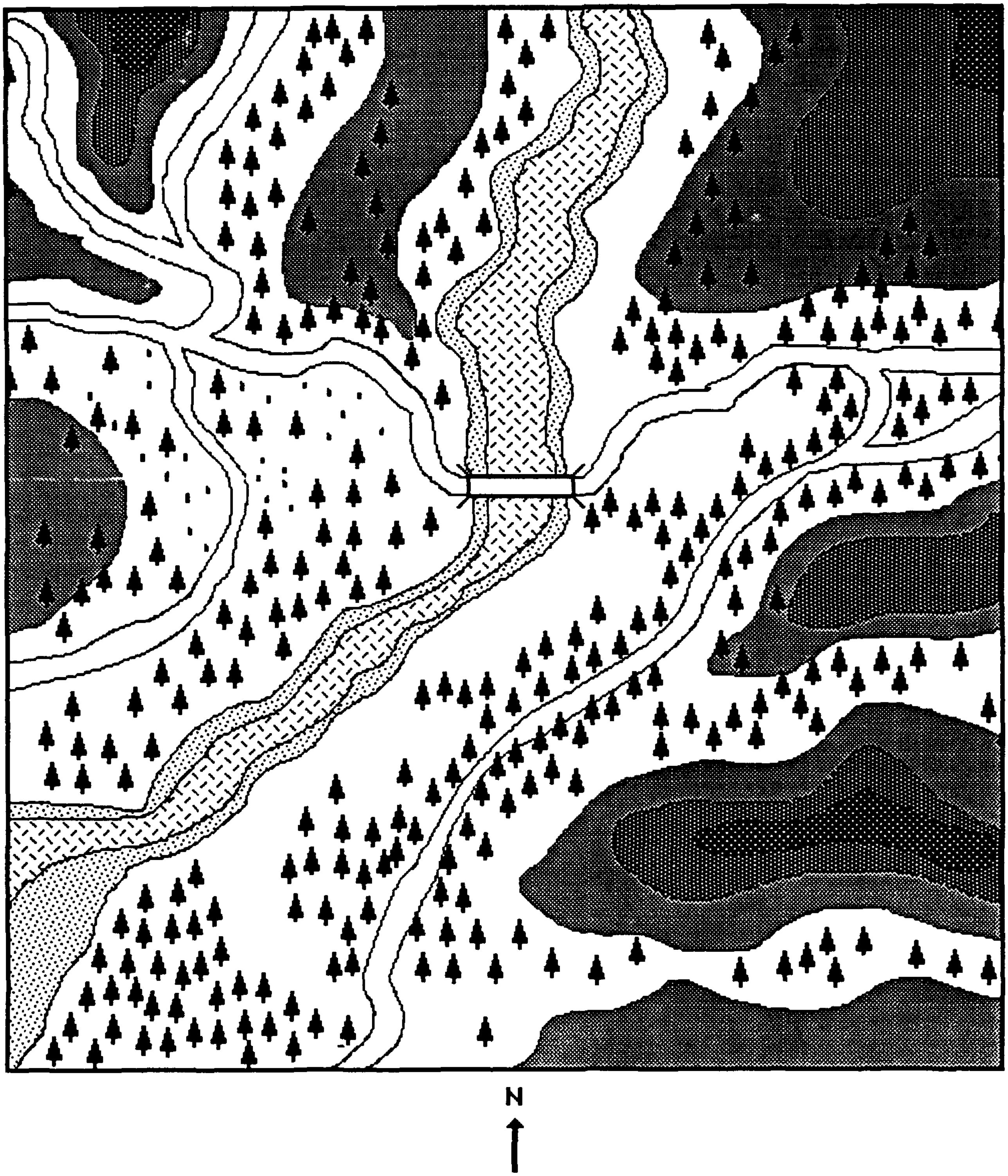


Figure 3. Battlefield for the Low-Level Complexity Scenerio

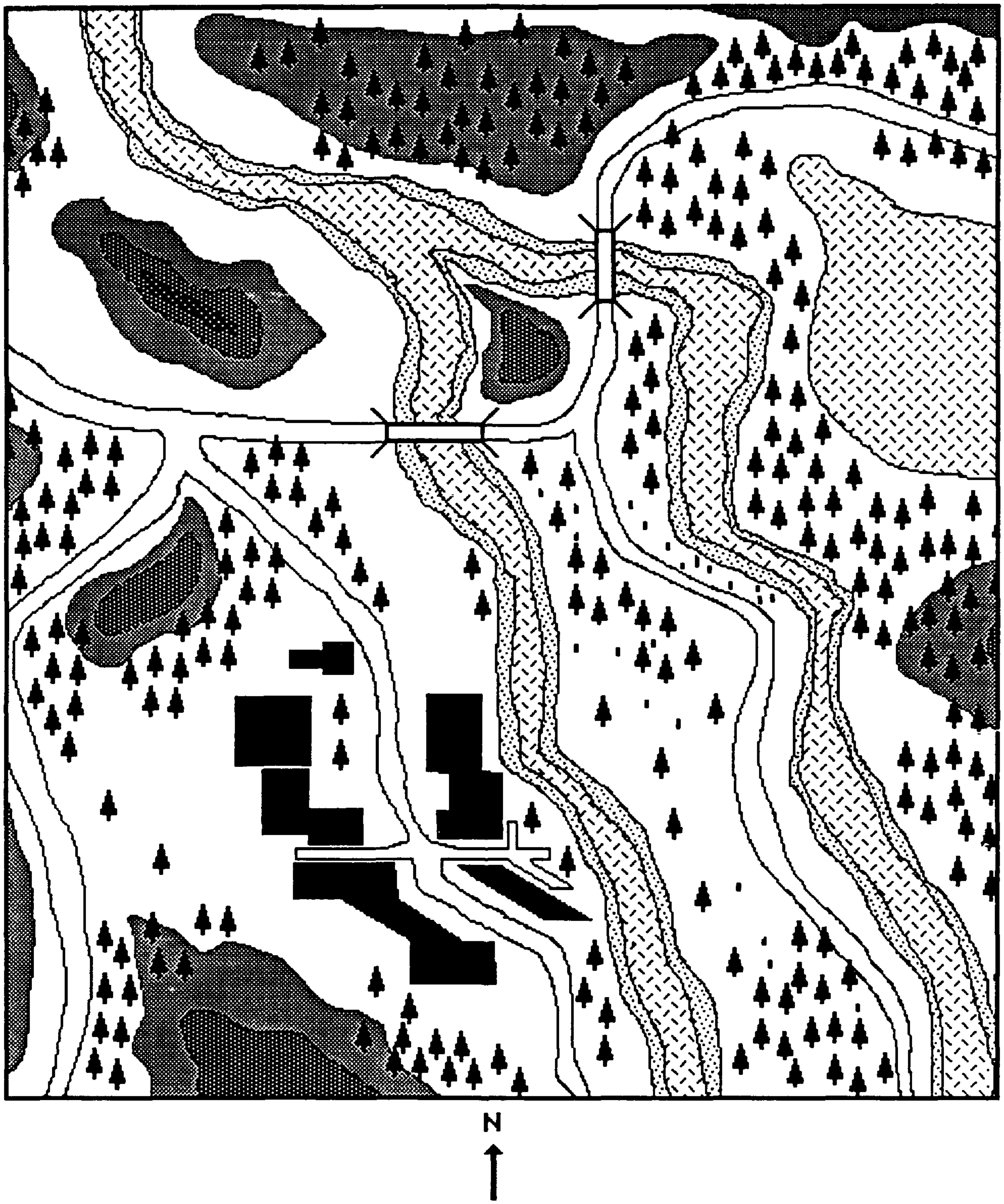


Figure 4. Battlefield for the Mid-Level Complexity Scenario

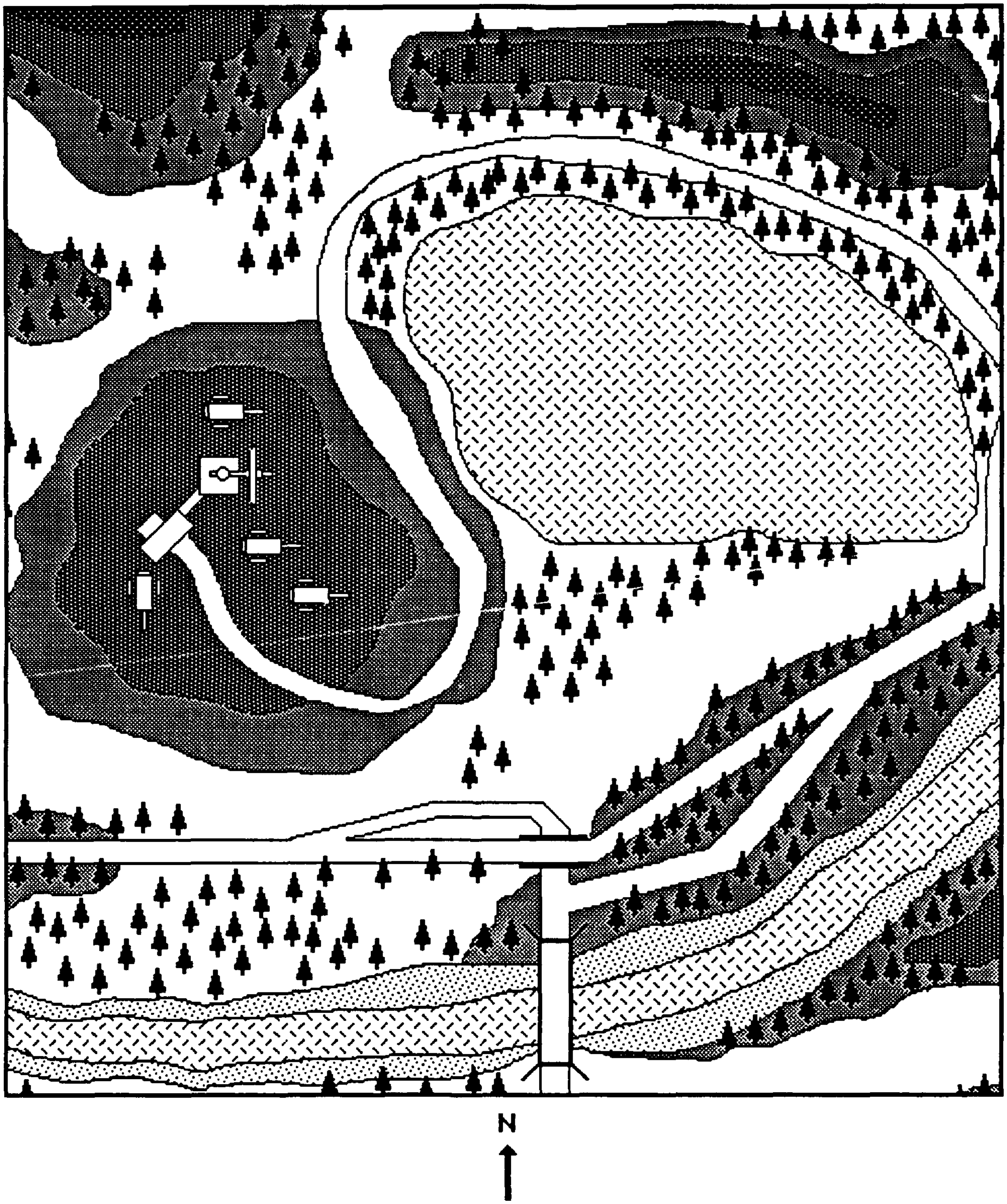


Figure 5. Battlefield for the High-Level Complexity Scenario

following items:

- estimate of enemy strength (i.e. number of tanks)
- estimate of enemy's destination (e.g., town, roadfork, bridge)
- estimate of enemy's objective (e.g., surround town, attack installation)
- estimate of the postions of the other subjects

Accuracy reflected how precise the subjects were in their assessment of the above categories (enemy strength, destination, objective, number of detections, and position of other subjects) as compared to the actual information contained in each of the categories.

These estimates are important elements of situation assessment. Military planners must know as much as possible about the enemy's disposition and activities. From this information, planners can derive estimates on enemy capabilities and intentions and incorporate these into their plans. Situation assessment (or situation analysis) is an extremely important element of battlefield planning because it is in this assessment process that the capabilities of the enemy must be identified and evaluated, and intentions inferred so that appropriate courses of action can be taken by friendly forces (Loeberg et al., 1986). Capabilities are the courses of action we believe the enemy can conduct, and intentions are the most likely courses of action we believe the enemy will carry out. The four estimates above were believed to be capable of providing the necessary information to the subjects on enemy capabilities and intentions all within the context of this study.

The second dependent measure was subjective workload ratings. Subjects rated the relative workload of each situation assessment session based on nine items adapted from Hart et al. (1984). The nine items were: overall workload, task difficulty, time pressure, performance, mental and sensory effort, physical effort, frustration level, stress level, and fatigue.

The third measure examined the level of agreement a subject had for the assessments of the other two subjects in the group.

<u>Battlefield scenarios</u>. As mentioned above, there were three different battlefield scenarios used in this study: low-level complexity, mid-level complexity, and high-level

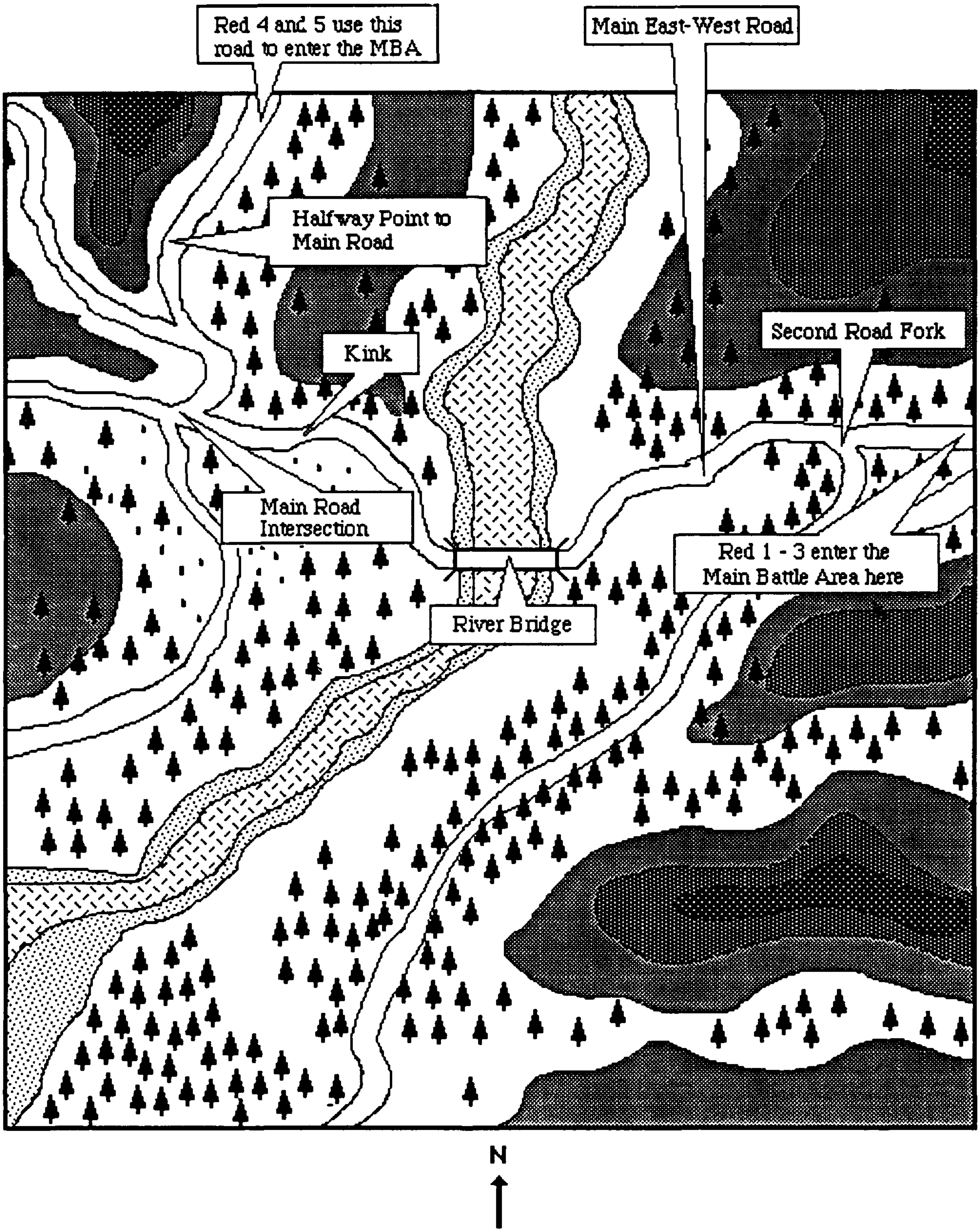


Figure 6. Key Battlefield Landmarks for the Low-Level Complexity Scenerio

complexity. The low-level complexity was used for a demonstration and practice seesion to get subjects familiarized with the operational requirements and characteristics of their computer systems. The medium- and high-level complexity scenarios were used for the actual experimental runs.

In the low-level complexity (LLC) scenario (see Figure 6), a total of five Red Force (enemy) tanks were employed. A column of 3 tanks entered the main battle area (MBA) from the northeast and proceeded westward on the main east-west road that took them across the river. Later, a column of 2 tanks emerged onto the MBA from the northwest and traveled south on the road located directly west of the river. These two tanks rolled down this road to the main road intersection and stopped there to wait for the other three tanks. The objective for these two Red Force tank columns were to meet up with each other at the major crossroads intersection on the western side of the MBA and then proceed westward.

For the mid-level complexity (MLC) scenario (see Figure 7), 10 Red Force tanks were used. The 10 tanks were divided into three columns: Red Column One contained 3 tanks , Red Column Two had 3 tanks, and Red Column Three had 4 tanks. The scenario unfolded as follows. Red Column One (Red 1-3) came out of the southwest MBA corner and moved up the road until it passed clear of the hill which nestles the eastern side of the road. At this point the tanks left the road and rumbled into the countryside, heading east toward the town. About halfway between the road and the town, the tanks stopped and positioned themselves so that each had its gun aimed toward the town.

When this was done, the other two tank columns appeared. The tanks of Red Column Two (Red 4-7) traveled up from the south on the road located in between the two rivers. Shortly after the appearance of Red Column Two tanks in the MBA, the tanks of Red Column Three (Red 8-9) rumbled into the MBA and began making their way down from the north along the western bank of the river.

Once Red Column Two made its way to the semi-clearing on the western side of the road, the tanks turned left, eased off the road, and headed toward the eastern bank of the western river fork. Upon reaching the bank, they stopped and aimed their guns at the town.

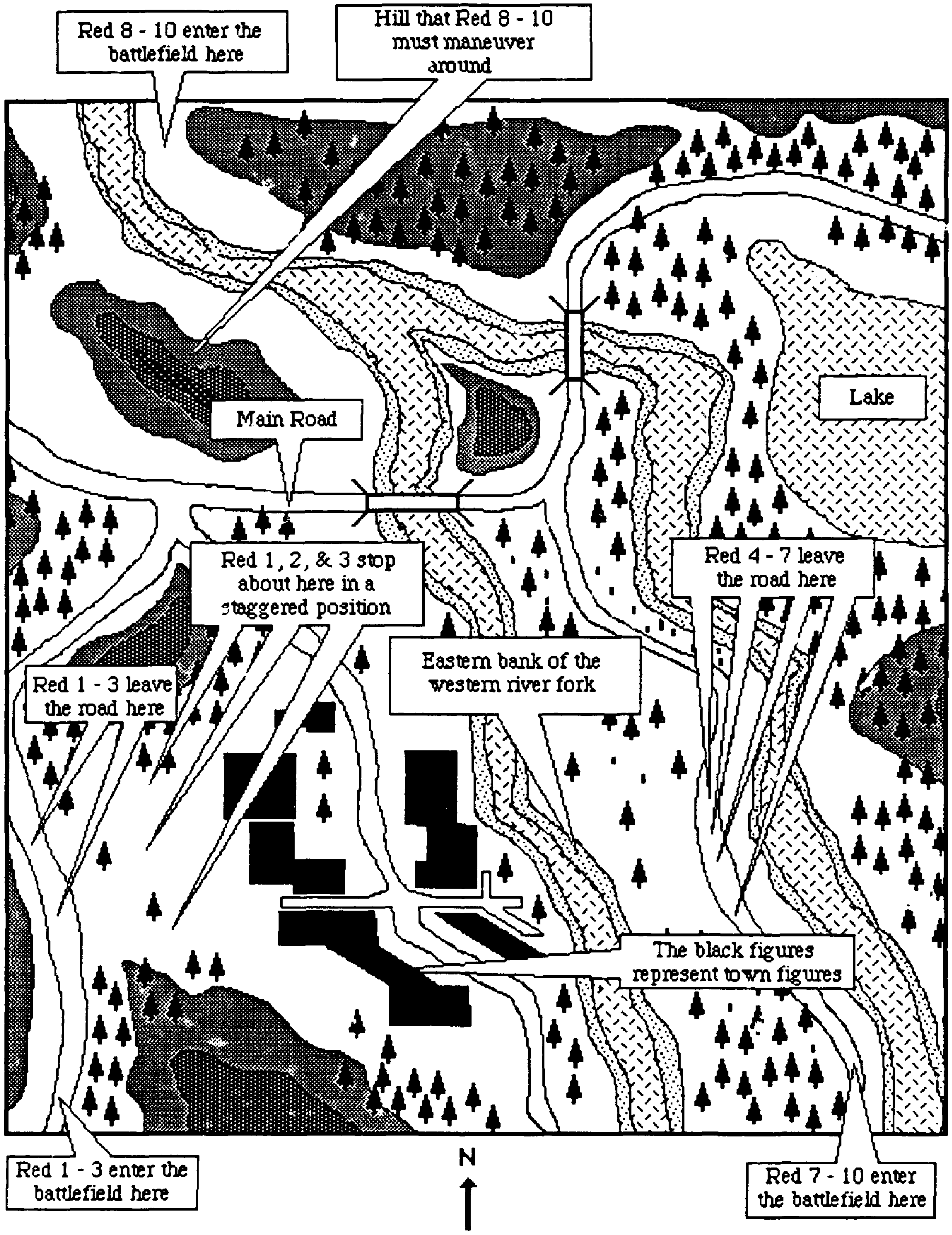


Figure 7. Key Battlefield Landmarks for the Mid-Level Complexity Scenario

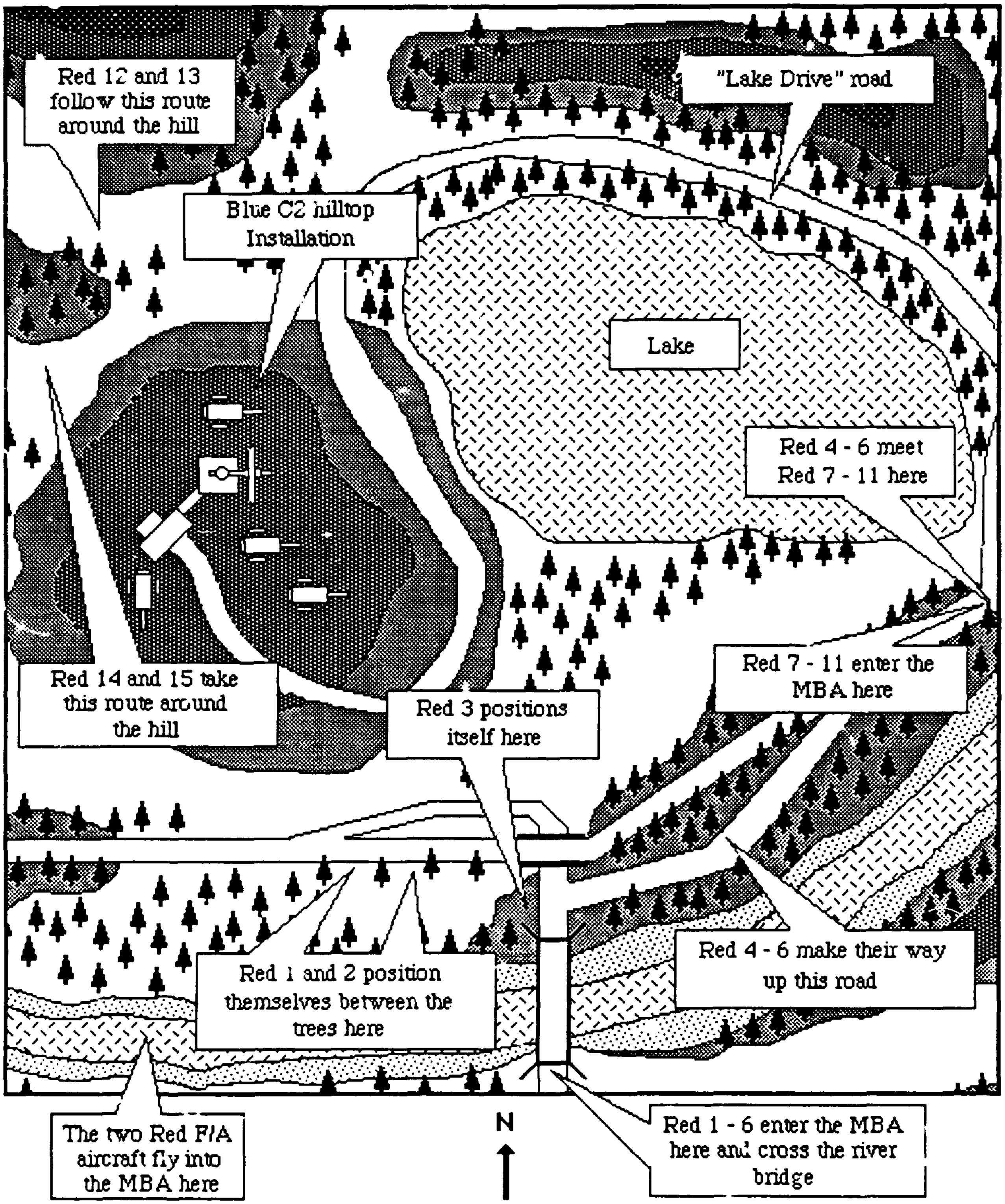


Figure 8. Battlefield for the High-Level Complexity Scenario

During this time, Red Column Three progressed downward along the western bank of the western river fork toward the northern end of the town.

The objective of the enemy was to surround the northern, eastern, and western flanks of the town and prepare for an offensive thrust. The scenario ended with three tanks on the western flank of town, four tanks on its eastern flank, and three tanks making their way down to position themselves on the northern flank.

In the high-level complexity (HLC) scenario (see Figure 8), Red Forces had three objectives. First, to cross the river and secure the bridge. Second, to have two tank columns rendezvous. Third, to surround and attack the Blue Force Command/Control installation.

Fifteen Red Force tanks and two Red Force fighter/attack aircraft were employed in this scenario. The scenario basically unfolded as follows. A column of six Red Force tanks (Red Column One with tanks 1-6) entered the MBA from the south-central portion of the field and proceeded north across the bridge. The first two tanks across the bridge positione themselves in the trees with their guns pointing up at the Blue C^2 installation. The third tank secured the bridge crossing by positioning itself at the entrance, and the fourth, fifth, and sixth tanks traveled northeast up the road to rendezvous with another tank column.

The three tanks traveling northeast rendezvoused with five other Red Force tanks (Red Column Two with tanks 7-11) at the road fork located in the eastern portion of the MBA. When the rendezvous was made, the eight tanks followed the road that took them around the lake toward the Blue Force hill. Prior to completely rounding the lake, the eight tanks stopped to keep out of range of Blue Force guns.

Shortly thereafter, four Red Force tanks (Red Column Three with tanks 12-15) stormed into the MBA from the west. These four tanks converged on the backside of the hill and slowly climbed it. As the tanks began climbing the hill, the eight tanks parked along the road lining the lake started moving. When this all occurred, two Red Force combat aircraft streaked out of the east and flew on a westerly heading to perform an air-to-ground attack on the Blue Force hill.

The scenario ended with all Red Force elements beginning their attack maneuvers.

2.1.5 Procedure. For the situation assessment session, each of the three subjects were placed at their own Macintosh workstation. The subjects' task was to observe and assess the developing situation, and then to arrive as best as they could at an interpretation of what was going on in the entire battlefield (not just what was going on in their own field of view). To achieve this goal, the subjects had to communicate with each other through their computer keyboards; they had to send each other information concerning battlefield developments during the situation assessment period.

Subjects were run in groups of three, and each group was randomly assigned to the experimental conditions. Groups of three subjects were run through a 10 minute situation assessment assignment on either the medium-level or high-level complexity scenario. For every scenario run, each subject saw a subset of the entire battlefield on their Macintosh screen (Figures 9 - 11), and their combined fields of view did not constitute the complete picture. In addition, the subjects did not know who saw what. The three different perspectives partially overlapped, and the orientation and amount of overlap remained constant throughout all three scenarios.

Before beginning the actual situation assessment session, subjects were given a thorough briefing on the objectives, procedures, requirements, and features of the battlefield situation assessment task. Upon completion of the briefing session, the subjects were seated at their Macintosh workstations and were run through the low-level complexity scenario. During this time, subjects familiarized themselves with the computer and the different features of the assessment task. Subjects could ask questions during this demonstration/practice session. This practice session generally lasted 40 minutes. When this session ended, the subjects were instructed to put on headphones in which low level white noise was piped through. This was done to mask out as much extraneous sounds as possible (e.g., keyboard sounds, exclaimations made by subjects).

After the demonstration/practice session, the actual experimental session was started. During an assessment period, if the "enemy" (MAC 0) detected a message transmission, MAC 0 sent a message to all three subjects. MAC 0's message read: "Warning! The enemy

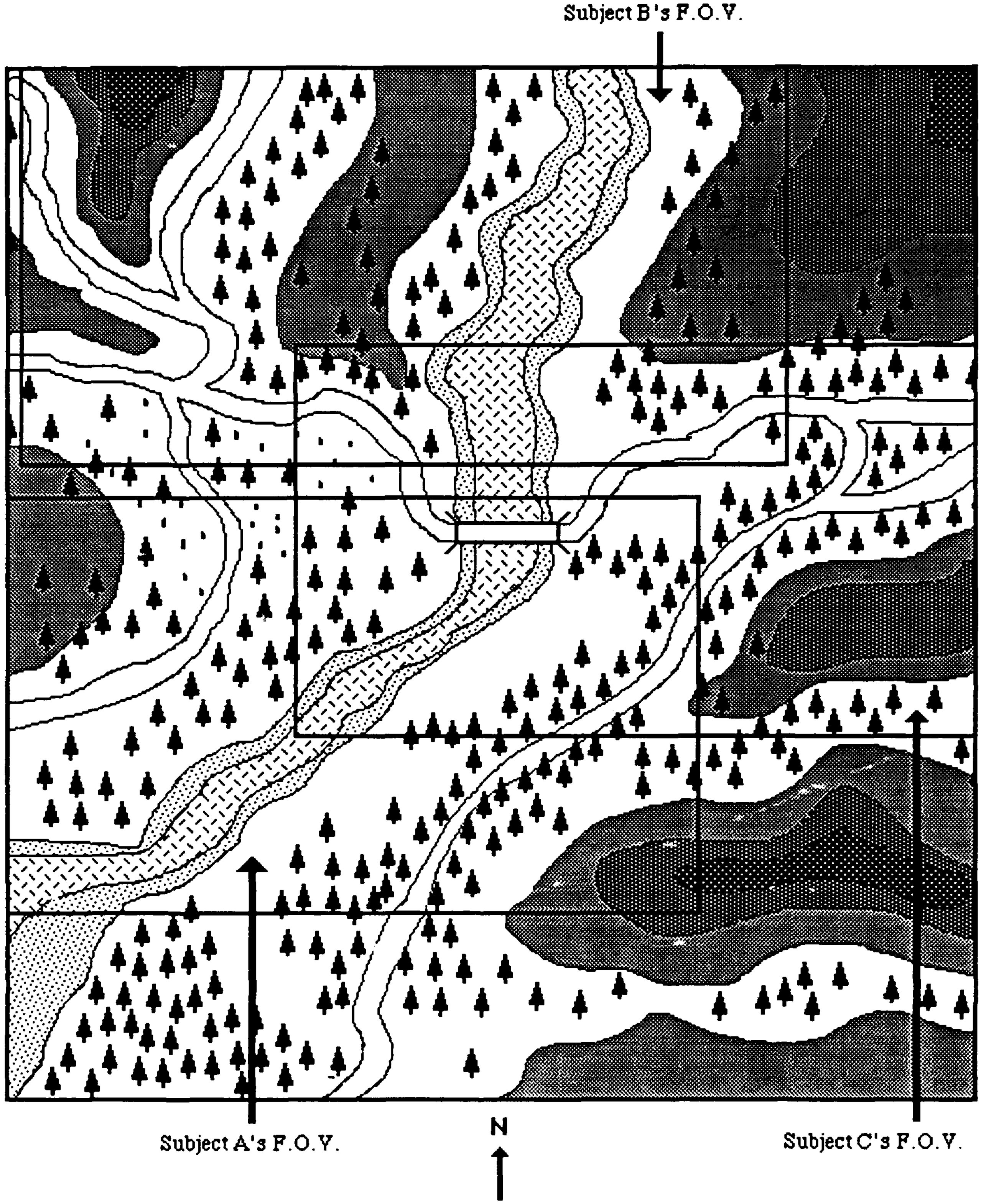


Figure 9. Subject's Field of View for the Low-Level Complexity Scenario

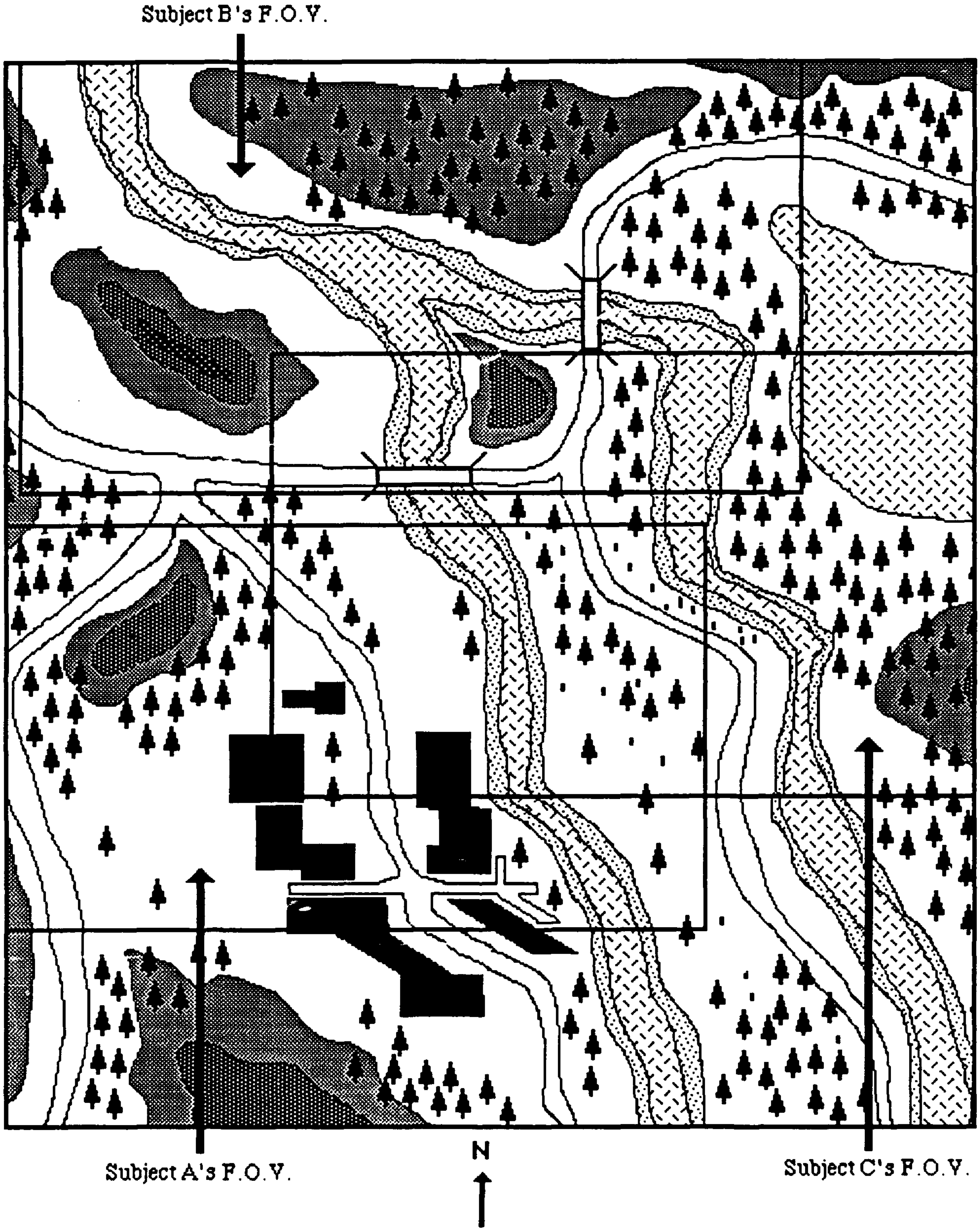


Figure 10. Subject's Field of View for the Mid-Level Complexity Scenerio

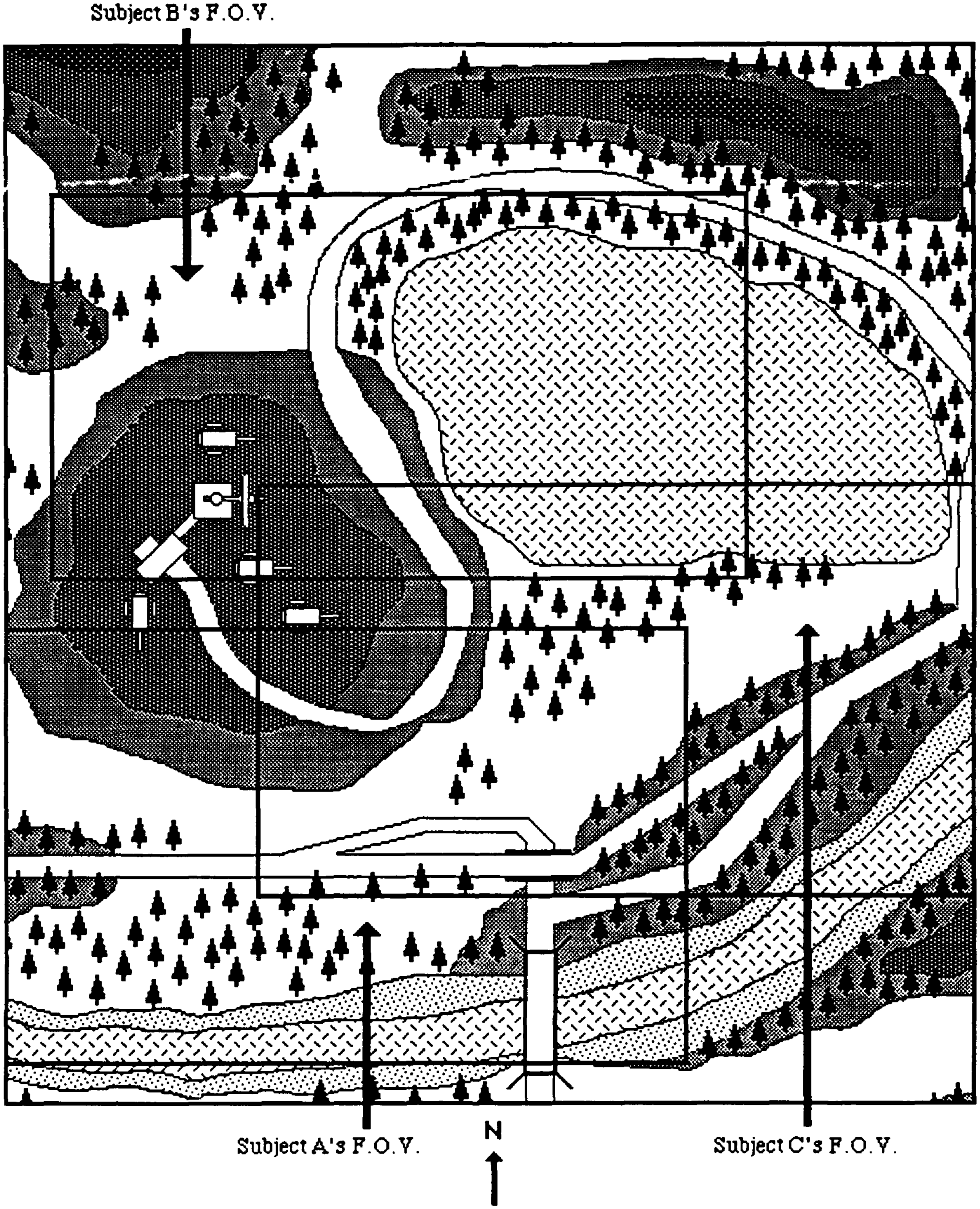


Figure 11. Subject's Field of View for the High-Level Complexity Scenerio

has possibly detected this message transmission." This message appeared in the subjects' main viewing screens for five seconds and then disappeared. MAC 0 kept count on how many times a detection was made. If the detection count for the entire group exceeded a total of 5 during a scenario, the initial consequence was the the blanking of the subjects' main viewing screens for 15 seconds. MAC 0 then immediately transmitted the following message to all three subjects: "Your group's message transmissions have been detected by the enemy. The enemy has initiated strong electronic countermeasures. The enemy will try to blank out your screen for several seconds, but you must complete your mission despite encountering strong ECM." After 15 seconds, the message disappeared and the subjects were returned to their normal screens to continue on with the situation assessment task. If a message transmission was detected again, the main screens went blank again for 10 seconds, and the message this time was: "Your group has run into some heavy electronic countermeasures. Your screen will be blank for several seconds." Hereafter, this second message appeared with the blank screen each time a message transmission was detected by MAC 0. The consequence for message detection, therefore, was blanking of the subjects' main viewing screens and loss of valuable time for situation assessment.

When a scenario was completed, the subjects were instructed by MAC 0 to do three things. First, the subjects were asked to individually assess the entire battlefield situation based on the information exchanged during the scenario viewing: "Based on the information you have, please state what you believe is going on in the battlefield." The subjects were required to type in their assessment using their Macintosh keyboards, and MAC 0 recorded each subject's interpretation.

For the second task, a subjective workload rating form (adapted from Hart et al., 1984) appeared on each MAC screen. Using the mouse, subjects rated the situation assessment task on nine items. After subjects completed the workload rating scales, they were routed to the third task which asked the subjects to rate each other's battlefield situation assessment: "Please rate how strongly you agree or disagree with each of your group member's assessment of the situation." The subjects were referred to a "blackboard" screen. On this "blackboard" appeared the above instruction, the subjects' individual situation assessment, and associated rating scales. For a given subject, his or her own Macintosh screen showed his or her own situation assessment first with the other two just below. There was no rating scale for the subject's own assessment, however, under each of the other two subjects' assessment, there was the question "How strongly do you agree or disagree with this situation assessment?" and just below it the following six point rating scale:

0	1	2	3	4	5
Strongly Disagree	Somewhat Disagree	Weakly Disagree	Weakly Agree	Somewhat Agree	Strongly Agree

Using the mouse again (simply through pointing and clicking), the subject rated his or her level of agreement with the other two subjects' assessment and gave a brief reason to support the particular rating. A major reason for this agreement rating was to compare the degree of agreement or disagreement among group members between BRODCOM and SELCOM groups. When all of the subjects finished with this task, the experimental session was completed.

3.0 RESULTS

Initial examination of the data reveals several interesting trends concerning the influences of human-computer communication protocols on group situation assessment. When comparing the total number of messages sent during a situation assessment scenario, there was a trend for Selective Communication groups to transmit more messages than Broadcast Communication groups. Figure 12 illustrates this. This difference was even more pronounced in the higher complexity scenario. In addition, both BRODCOM and SELCOM groups that were assigned to the 50% detection level showed the tendency to have a lower

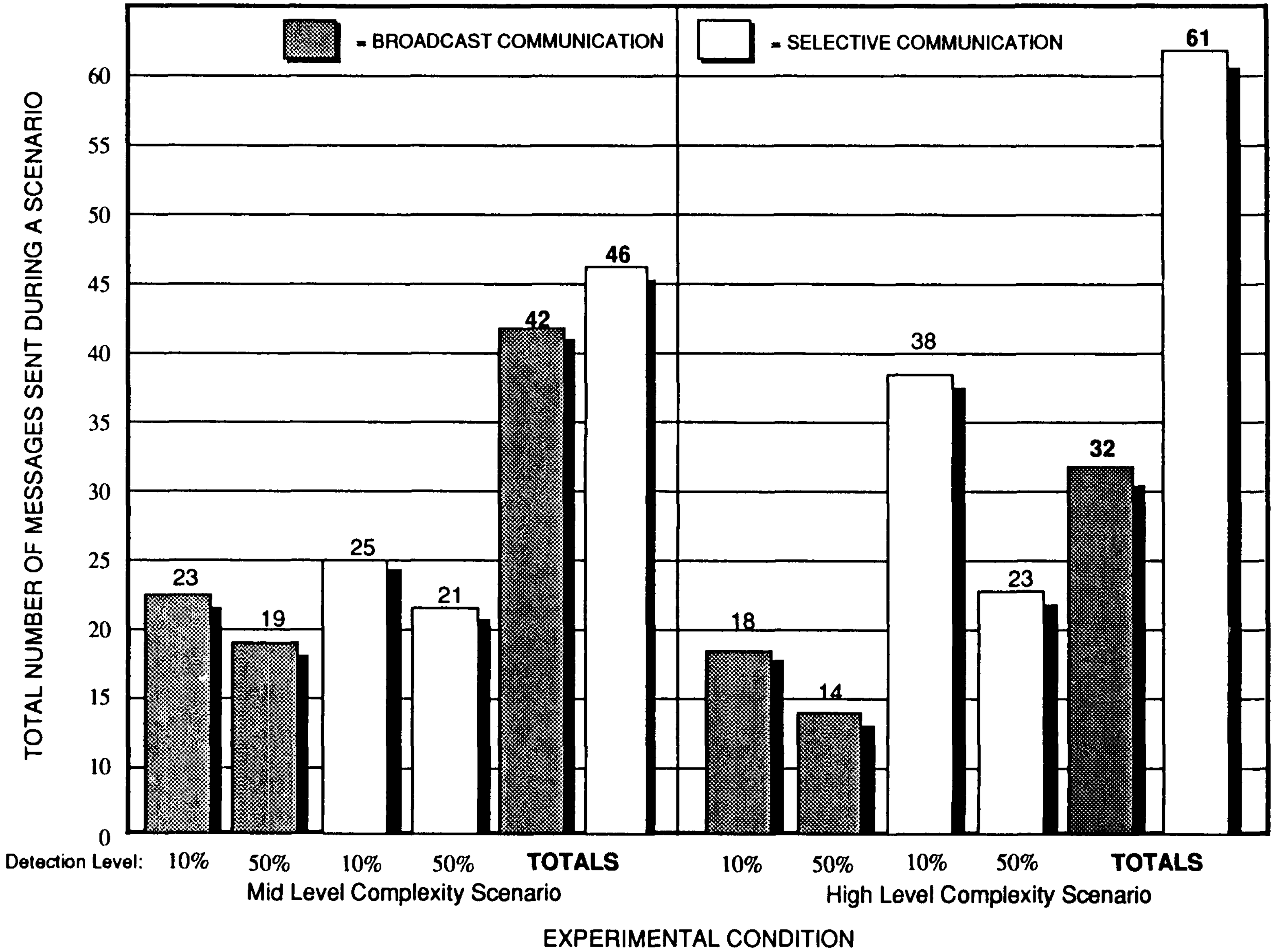


Figure 12. The Total Number of Messages Sent During a Situation Assessment Session.

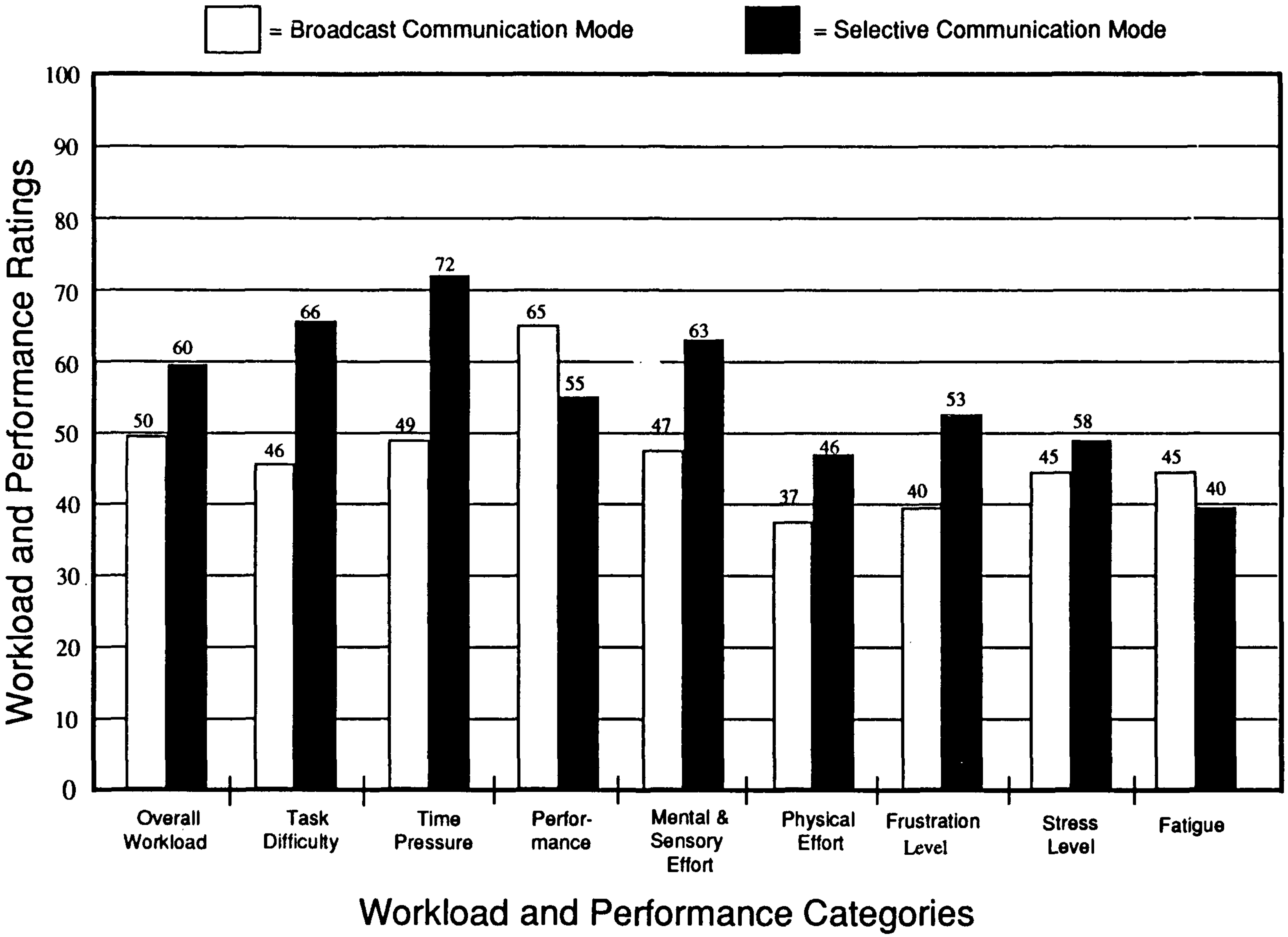


Figure 13. Workload and Performance Ratings given by subjects in the Mid-Level Complexity Scenario at the 10% detection level.

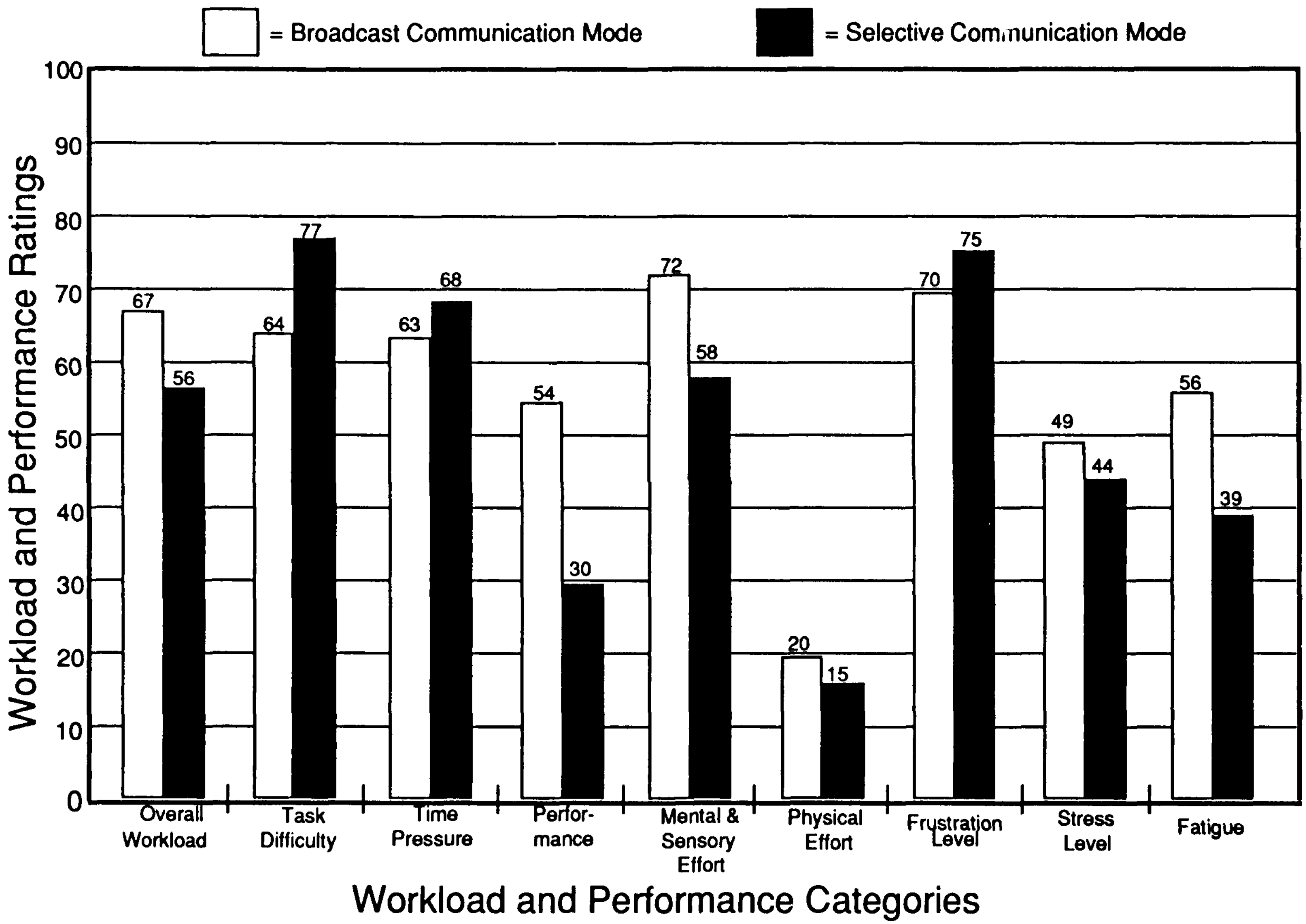


Figure 14. Workload and Performance Ratings given by subjects in the Mid-Level Complexity Scenario at the 50% detection level.

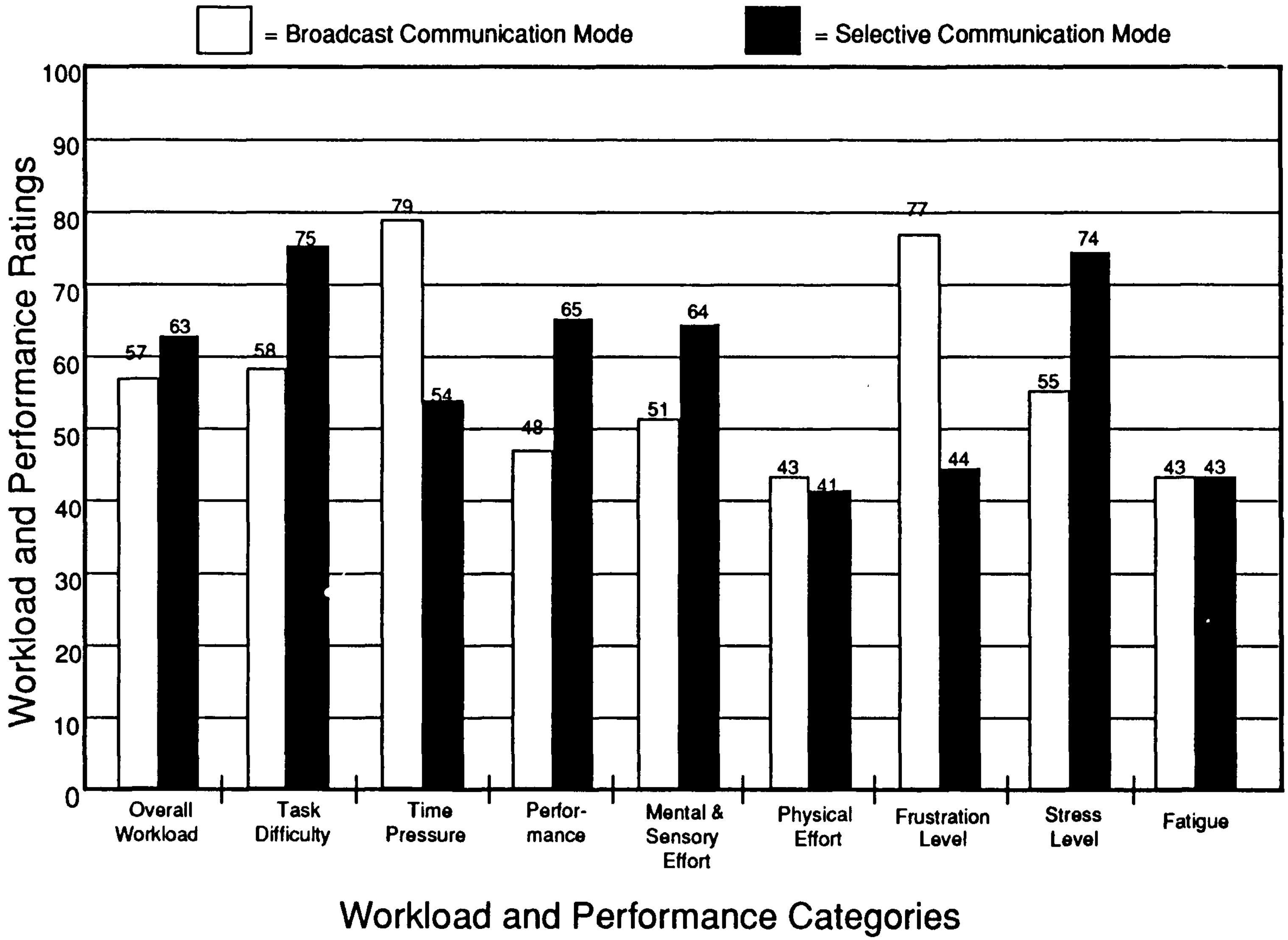


Figure 15. Workload and Performance Ratings given by subjects in the High-Level Complexity Scenario at the 10% detection level.

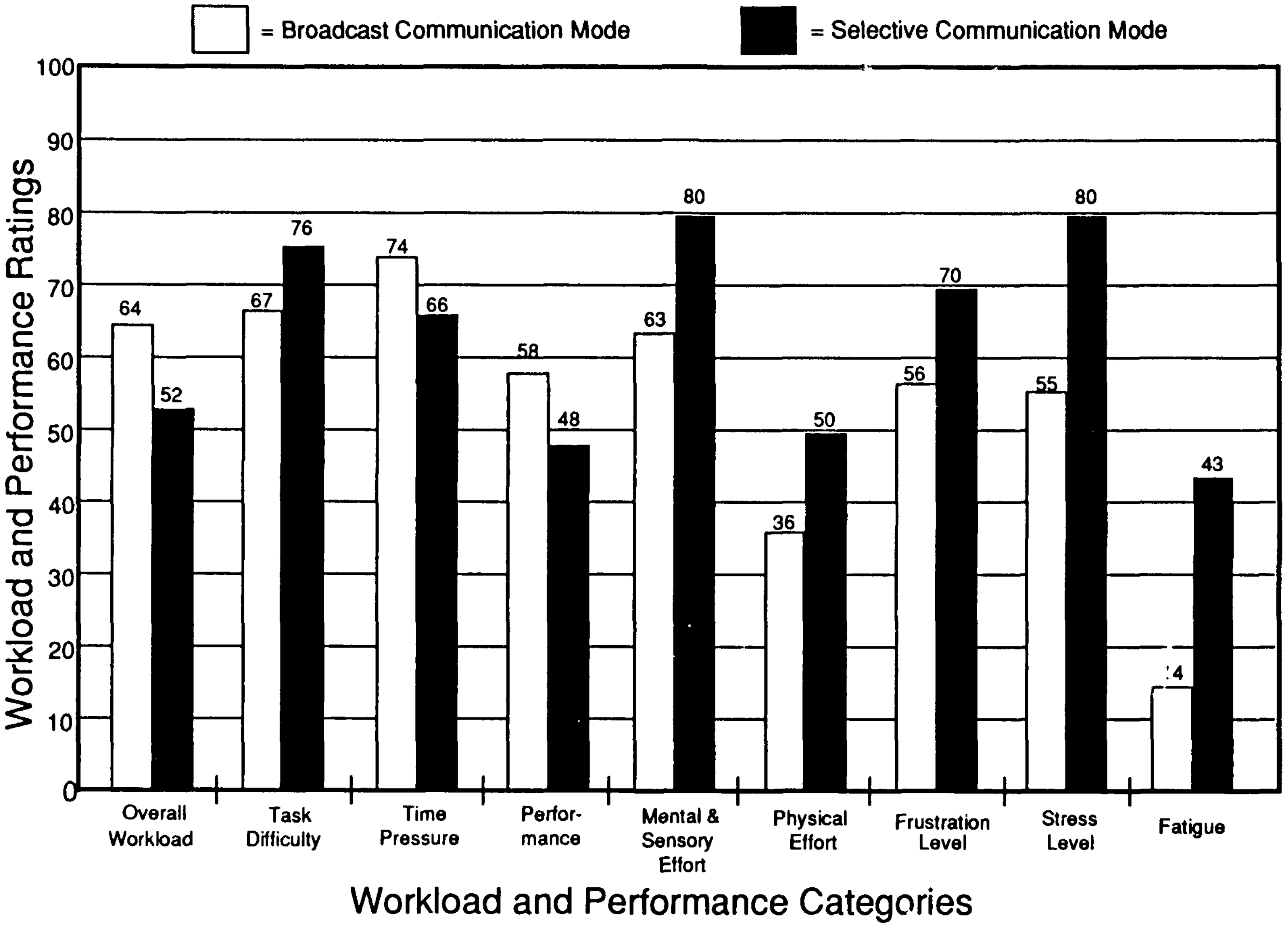


Figure 16. Workload and Performance Ratings given by subjects in the High-Level Complexity Scenario at the 50% detection level.

total number of message transmissions than BRODCOM and SELCOM groups assigned to the 10% detection level. It was not known whether this was due to the greater number of screen blackouts by Mac 0 (total of 27 blackouts for 50% groups versus total of 9 blackouts for 10% groups) or to group perception that the blackouts will affect their overall situation assessment performance score.

Interesting trends were found in the workload and performance ratings (see Figures 13 - 16). Overall, the Broadcast Communication groups gave higher ratings for their performance than did the Selective Communication groups. From initial subjective analyses of the subjects' assessments, BRODCOM subjects appeared to have obtained a more complete and accurate picture of the entire situation than did SELCOM subjects. Communication protocols seemed to have some influence on subjects' perception of the situation assessment task. Overall, BRODCOM subjects on the average gave lower ratings for task difficulty, mental and sensory effort, frustration level, and stress level.

The degree of agreement between group members appeared to be influenced by detection probability. In both the mid-level and high-level complexity scenarios, agreement levels were higher for subjects in the 10% condition than in the 50% condition. For the MLC scenario, BRODCOM subjects in the 10% condition gave an average agreement rating of 4.5, on a scale of 0 to 5 (see procedure section). The value 4.5 roughly translates into a strong agreement rating. BRODCOM subjects in the 50% detection level condition had an average agreement level of 3.0. This translates into a weak agreement among subjects. For SELCOM subjects in the MLC scenario, subjects in the 10% detection condition responded with a rating of 3.8, meaning an average level of agreement. SELCOM subjects in the 50% detection condition averaged a 3.0 agreement level—weak agreement. In the HLC scenario, BRODCOM 10% subjects gave an average rating of 3.0 as compared to 2.8 given by BRODCOM 50% subjects. SELCOM 10% subjects responded with an average of 4.0 while

SELCOM subjects came with an average agreement rating of 3.6.

4.0 DISCUSSION

This was an entry study designed to find out what influences different human-computer communication protocols had on group situation assessment performance. Several noteworthy trends were found concerning message transmissions, perceived performance, and level of agreement between group members. Data on individual group members' situation assessments have shown a trend for BRODCOM assessments to be more complete and accurate.

The basic experimental design can be modified in order to examine this issue of human-computer influences on situation assessment in greater depth. More experimental variables and better data collection can be implemented into the system. One specific item that may be changed is the requirements for situation assessment. More strict requirements may be designed for subjects to follow when they are typing in their assessment. This may make the whole process more standardized so that statistical analysis of situation assessment content can be conducted.

One problem that was encountered during data collection was the reliability of subjects to show up for the experimental session. For each session, three subjects were needed. In a number of instances, only one or two subjects arrived for the experiment. When this occurred, a scramble for additional subjects ensued; if none could be found, the session was written off. Methods of ensuring more reliable subject turnout are being looked into.

Some significant trends have been observed in this initial study of human-computer situation assessment. Further study in this area has the potential to provide data that can help establish guidelines to assist the Army in finding optimal communications protocols and organizational structures for gathering and analyzing battlefield information, in addition to making the most effective use of interactive, mutually assistive, human-computer resource combinations.

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Final Report--Part Two

GROUP ACQUISITION OF DYNAMIC CONTROL SKILLS IN A FLUID LEVEL ADJUSTMENT PROBLEM

Abstract

Experiments were conducted in a distributed problem-solving context that focused on supervisory process control and the study of group problem-solving and decision-making in a computer generated dynamic scenario with limited observability and controllability. The experiments synthesized observations from two sources, viz., single operator control simulations of human process control problem-solving and acquisition of process control skills. Experimental questions concerned the manner in which variation in partitioned observables and controllables, structure and number of communications pathways and workload variables affected individual performance.

The primary focus and goal of the study was toward enhancing current understanding of human behavior in slow response systems. It was also directed toward aiding with concepts for the design and analysis of distributed problem-solving and decision-making networks.

The experiments placed three subjects in command of a process control problem. Each subject interacted with the group and the situation through his/her respective computer workstation. The problem situation was purposely created to minimize, but not trivialize, the learning needed by subjects as they became familiar with their assigned roles within the network. Further, their channels of communication and permitted actions were restricted and structured to provide data for a statistical evaluation of the performance of each group, per trial, with variations in the scenario structure. The variations included the communication hierarchy, the number of control input paths, and the observability and controllability partitioning. Dependent variables included a time integrated, squared, regulation error, message and control input frequencies and serial connectivity (action transition matrices), and post-trial subject surveys.

This research confirmed and extended the body of understanding of humans in distributed problem-solving situations by finding that: 1) chain groups reached their respective "steady-state" final time performance values in fewer trials and had denser communication transition matrices than circle groups; 2) chain groups tended to focus on short term control strategies; 3) a very small increase in the number of control input paths decreased group performance by overloading the operators; and 4) individuals at "hub" communication stations showed the most positive attitudes and tended to evolve leadership roles.

1.0 INTRODUCTION

The motivation for this investigation was to attempt to develop a better understanding of the ways and the degree that the acquisition of distributed dynamic control skills of a group is affected by: a) the variation in partitioned observables and controllables; b) the communication network of the group; c) the number of control input paths. The experiments synthesized the work of Morris, Rouse and Fath, 1985; Morris and Rouse, 1985; Knaeuper and Rouse, 1985; Mann and Hammer, 1986, in human problem-solving in process control using a single operator simulation called "PLANT" with the work of Moray, Lootsteen, and Pajeck, 1986, on acquisition of process control skills. The latter work used a simulation extension of the method of Crossman and Cook, 1974. The results were based on a single operator situation and were described with action transition graphs. In the present report we have attempted to extend the body of understanding of humans in distributed problem-solving situations, particularly the work reported by Bavelas,1951, and by Parsons, and others at RAND, 1972, by partitioning the observables and controllable states and inputs of the process among a networked group of operators.

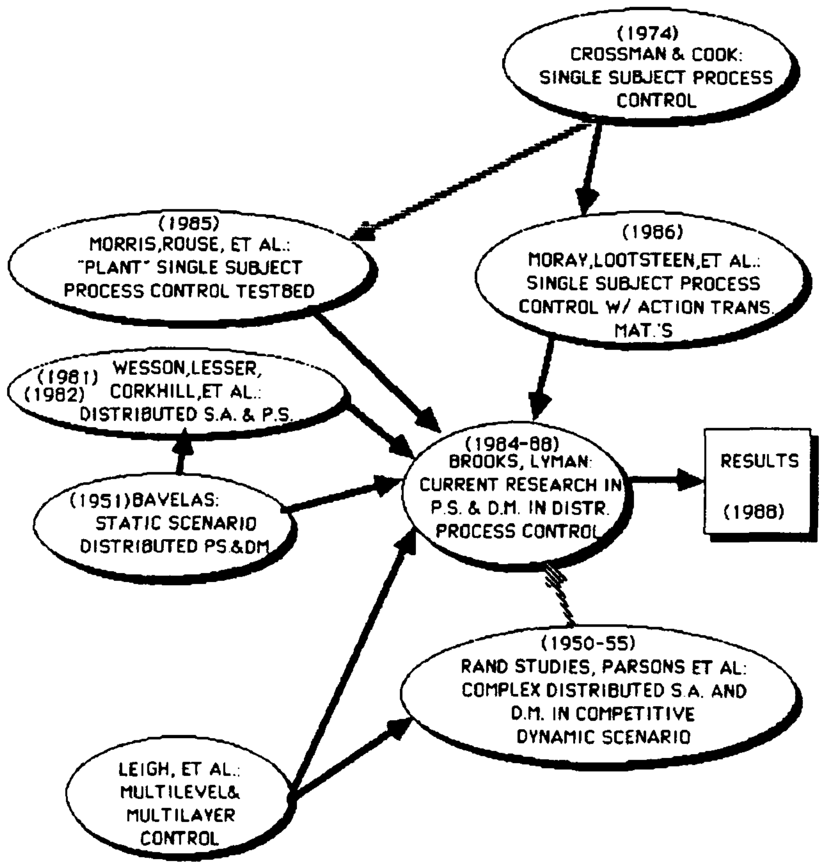


Figure 1. Flow Diagram of Closely Related Research

Insights were provides by the works of Wesson, et al., 1981, and Lesser and Corkill, et al, 1982, 1983. Fundamentals in process control were drawn from Leigh, 1985. Figure 1 illustrates the relationships of the research with a digraph.

2.0 EXPERIMENT

The subjects were placed in isolation cubicals with headphones playing white noise. From these workstations, all communication within the group and all observations and control inputs were made to the participants through Macintosh computers as shown in Figure 2. The simulation had either chain or circle commu-

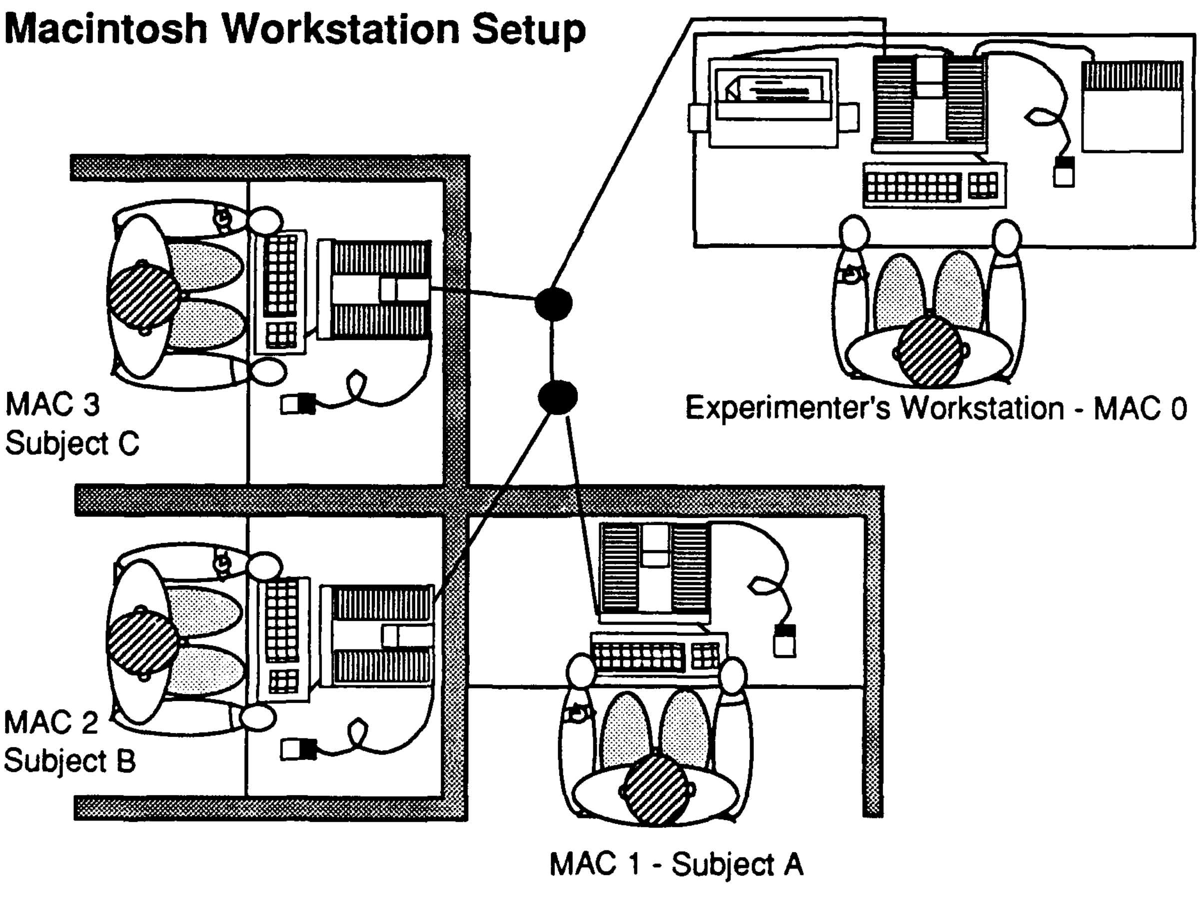
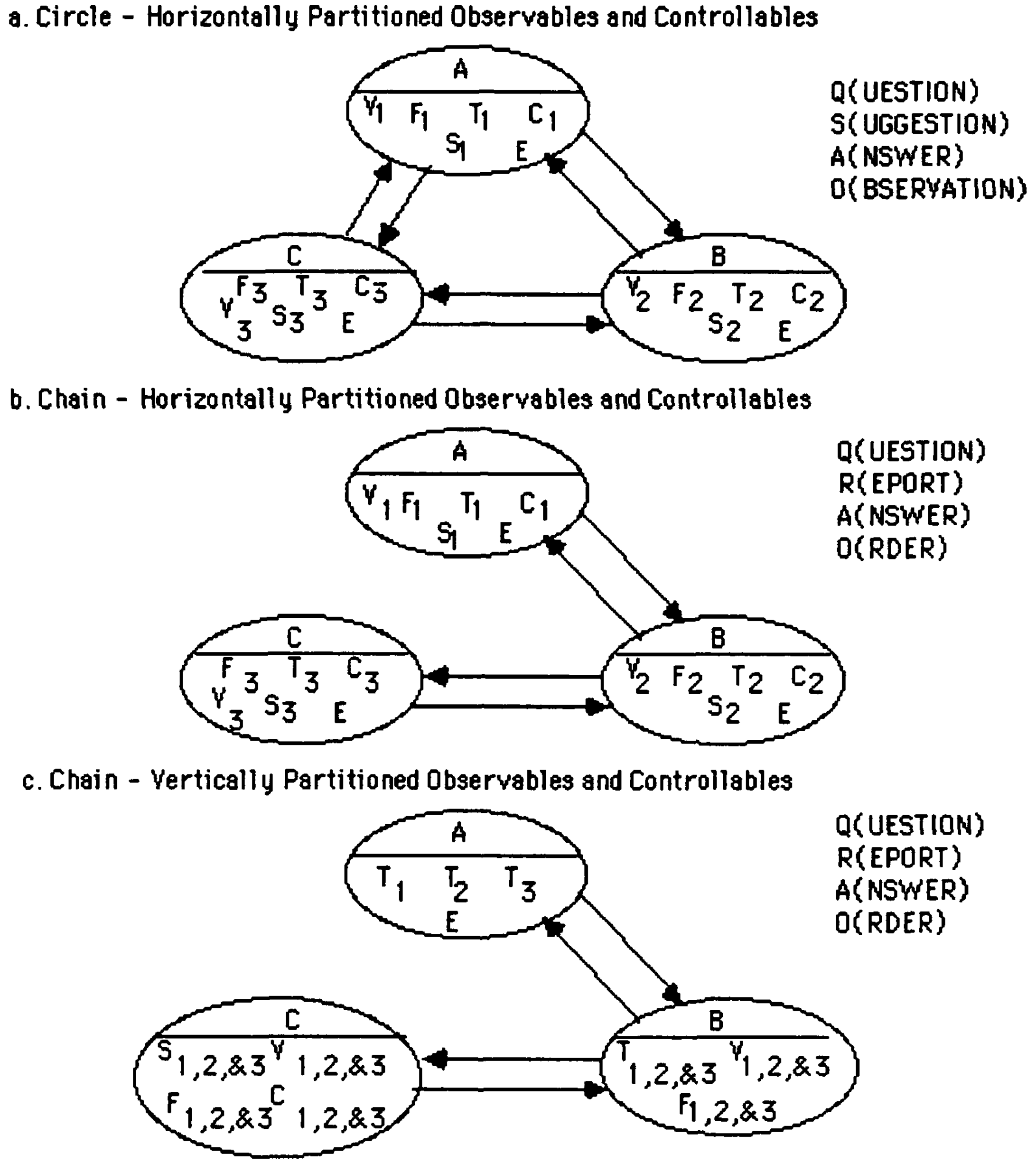


Figure 2. Macintosh Workstation Setup



LEGEND

F_i = OBSERVE PIPE FLOWS EXITING TANKS OF ROW i
T_i = OBSERVE TEMPERATURE OF TANKS OF ROW i
V_i = OBSERVE VOLUME OF TANKS OF ROW i
S_i = OBSERVE PIPE FLOW EXITING SOURCES OF ROW i
E = OBSERVE ENERGY EOORO RATE OF SINKS OF ALL ROWS
C_i = CONTROL PIPE FLOWS EXITING SOURCES OF ROW i

Figure 3. Communication, Observation and Control Structures: a) Structure i, b) Structure II and c) Structure III

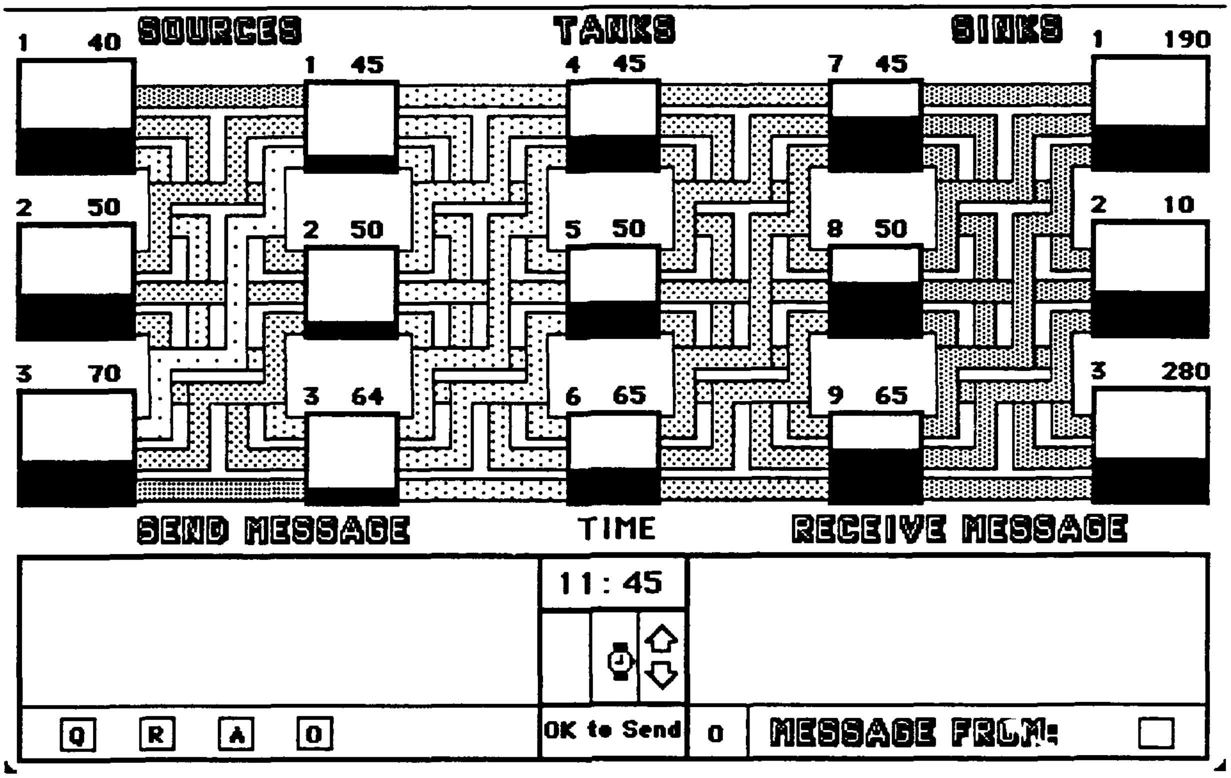


Figure 4. Overall Layout

nication structures. Figure 3 shows how the observables and/or controllables were partitioned either horizontally or vertically. A "god's eye-view" of the simulation is shown in Figure 4. Heated/cooled "water" traveled from sources on the far left through pipes and intermediate tanks to sinks on the far right. Above each source icon was the source identification number and the temperature of the exiting water. Above each tank icon was the tank identification number and the temperature of the exiting water. Above each sink was the sink identification number and the error in the exiting energy flow rate. Subjects were instructed to drive the error values to zero as soon a possible and keep them there throughout each of the twelve minute trials.

The information was partitioned such that subjects only observed and/or controlled a portion of the dynamic scenario. Figure 5 shows an example of what subject station A might have seen one hundred and seven seconds into the simula-

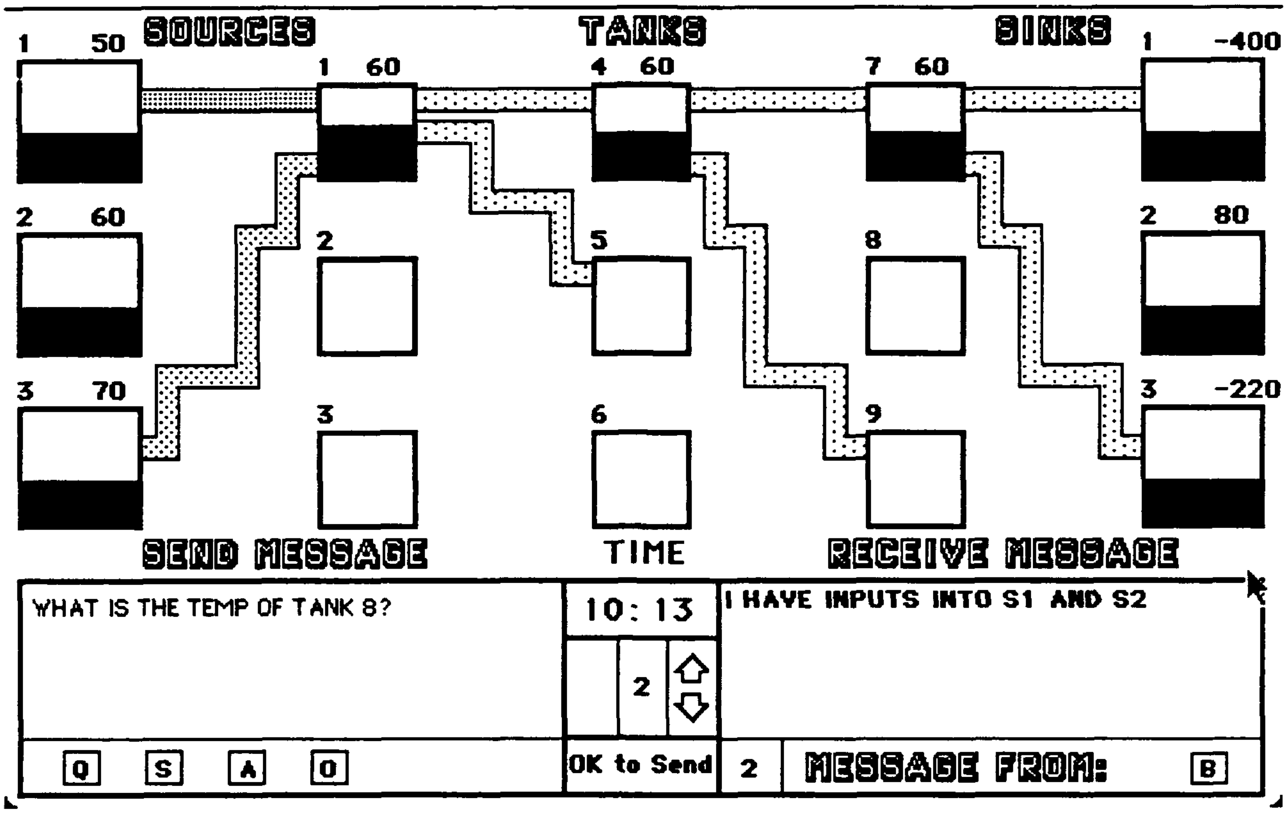


Figure 5. Subject station A, Low Pipe Count

tion. It is clear that communication on the network was vital to the sharing of information in order to successfully drive and maintain the error signals at a value of zero.

The dynamics the simulation were based on first order flow models for an idealized fluid with as many as three input pumps and three output pumps. The conceptual system in shown in Figure 6. Pipe flows could be controlled by the subjects using the mouse and pointing and clicking. The block diagrams for the energy and volume states are shown in Figures 7 and 8 respectively. For simplicity, where E = k V T, the value of k was set to unity. Also, to conserve mass. the pipe flow into a tank was shut off when the volume maximum was achieved. The pipe

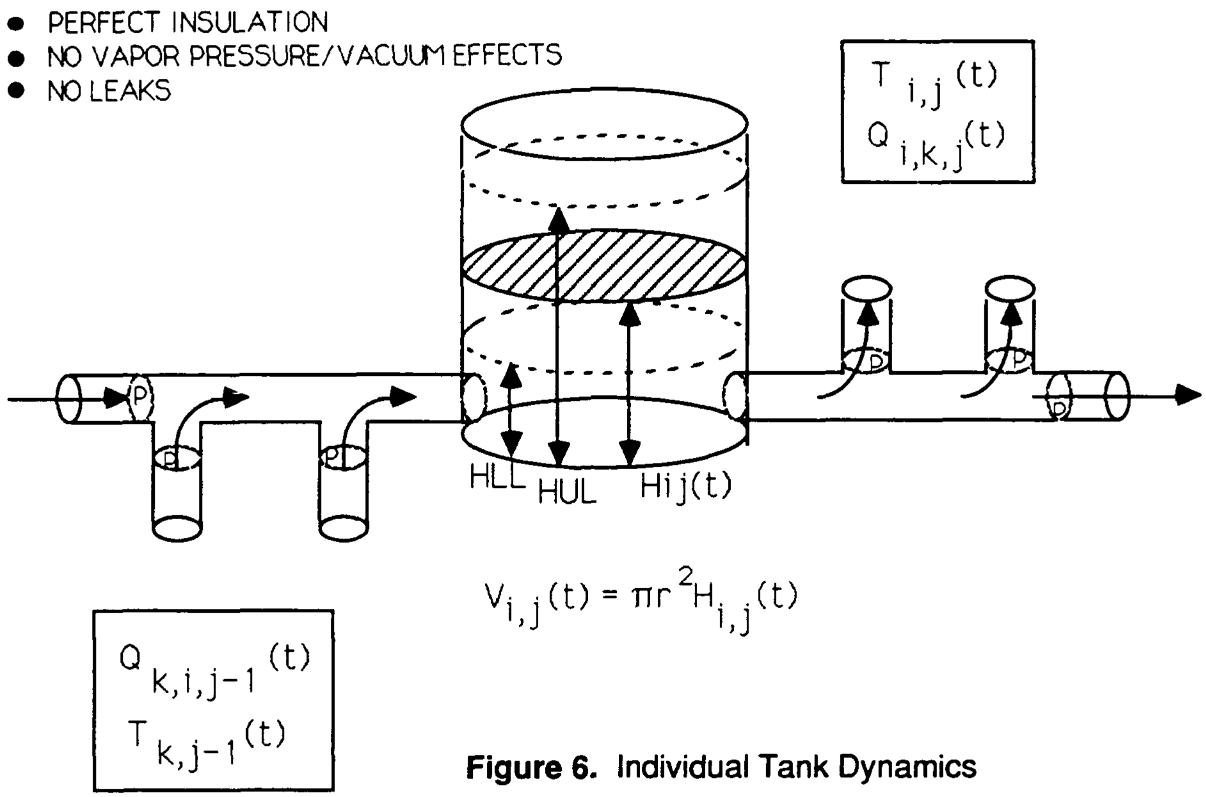


Figure 6. Individual Tank Dynamics

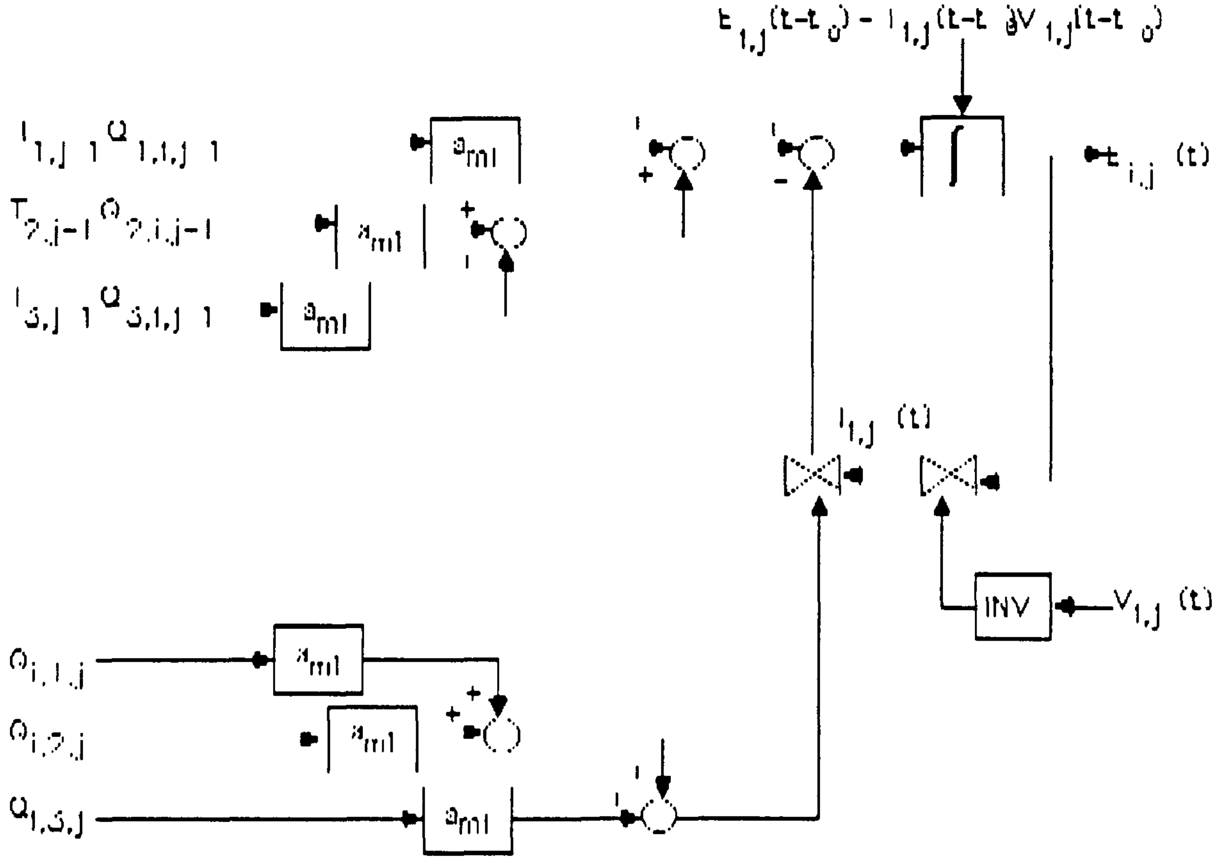


Figure 7. Energy State Equation Block Diagram

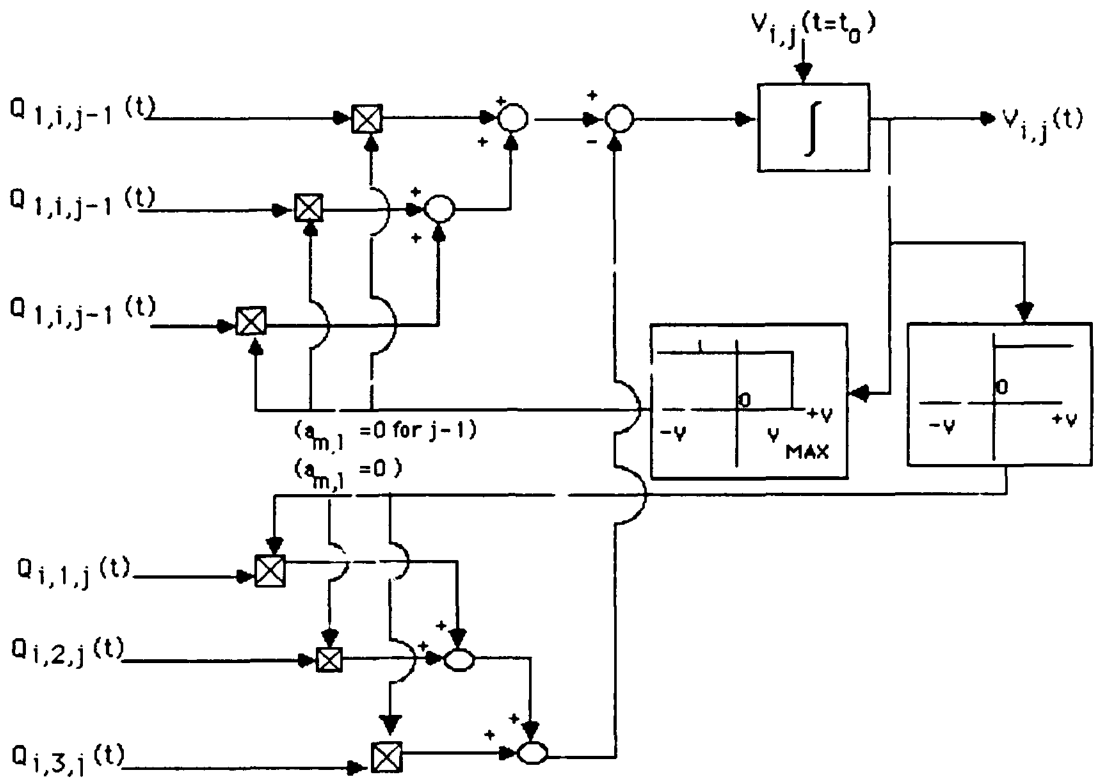


Figure 8. Volume State Equation Block Diagram

To establish a performance index, the following definitions are made:

$$[Q_{OUT}] = \begin{bmatrix} Q_{1,1,3} & Q_{2,1,3} & Q_{3,1,3} \\ Q_{2,1,3} & Q_{2,2,3} & Q_{2,3,3} \\ Q_{3,1,3} & Q_{3,2,3} & Q_{3,3,3} \end{bmatrix}$$

$$T_{OUT} = \begin{bmatrix} T_{1,3} \\ T_{2,3} \\ T_{3,3} \end{bmatrix} \qquad [M] = \begin{bmatrix} M_{11} & 0 & 0 \\ 0 & M_{22} & 0 \\ 0 & 0 & M_{33} \end{bmatrix}$$

$$S\dot{E} = \begin{bmatrix} S\dot{E}_1 \\ S\dot{E}_2 \\ S\dot{E}_3 \end{bmatrix} \qquad \underline{S\dot{E}} = [Q_{OUT}]\, T_{OUT} - \underline{\dot{E}}_{REF}$$

$$\dot{E}_{REF} = \begin{bmatrix} \dot{E}_{1\ REF} \\ \dot{E}_{2\ REF} \\ \dot{E}_{3\ REF} \end{bmatrix}$$

$$\text{PERFORMANCE INDEX} = \text{P.I.} = \int_{t_o}^{t_f} S\dot{E}^T [M]\, S\dot{E}\, dt$$

flow out of a tank was shut off when the volume minimum of the tank was achieved. Thus, the simulation had "fast" linear dynamics and both "fast" and "slow" nonlinear dynamics.

After each trial, a survey was taken by the workstation software on topics of overall workload, task difficulty, time pressure, performance, mental and sensory effort, physical effort, frustration level,and fatigue. Figures 9 and 10 show reprsen-

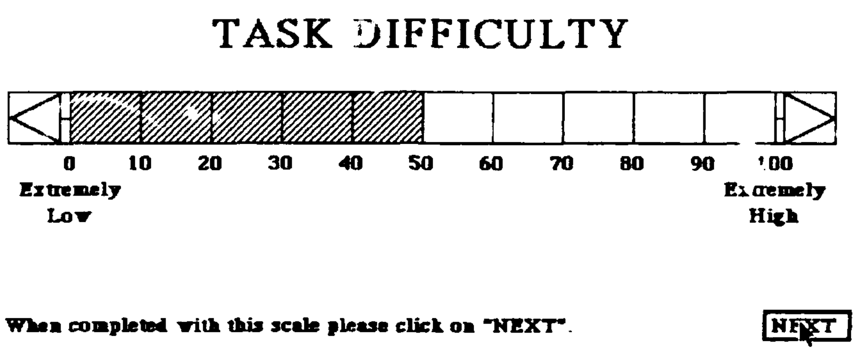


Figure 9. Task Difficulty Screen

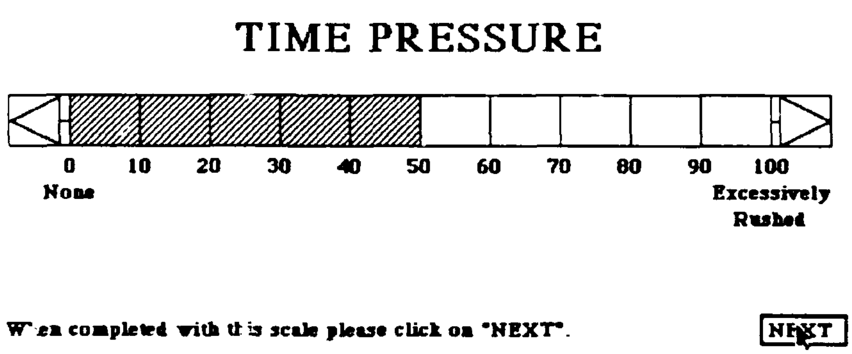


Figure 10. Time Pressure Screen

titive examples of the task rating bars. The shaded areas could be changed by "dragging" with the mouse.

2.1 Statistical Design: Each group of three subjects were administered three repeated trials and were thus "trained" with either structures I or II and with either two (L) or three (H) pipes exiting each tank . The fourth trial was a different structure and/or pipe count and structure III was in as one of the options. The experimental design plan is shown in Figure 11.

Statistical investigations were conducted using AXBXCX(DXs) ANOVA's with repeated trials for survey topics, communication and control frequency. For the performance indices and the group control frequencies, a AXBX(CXs) design was

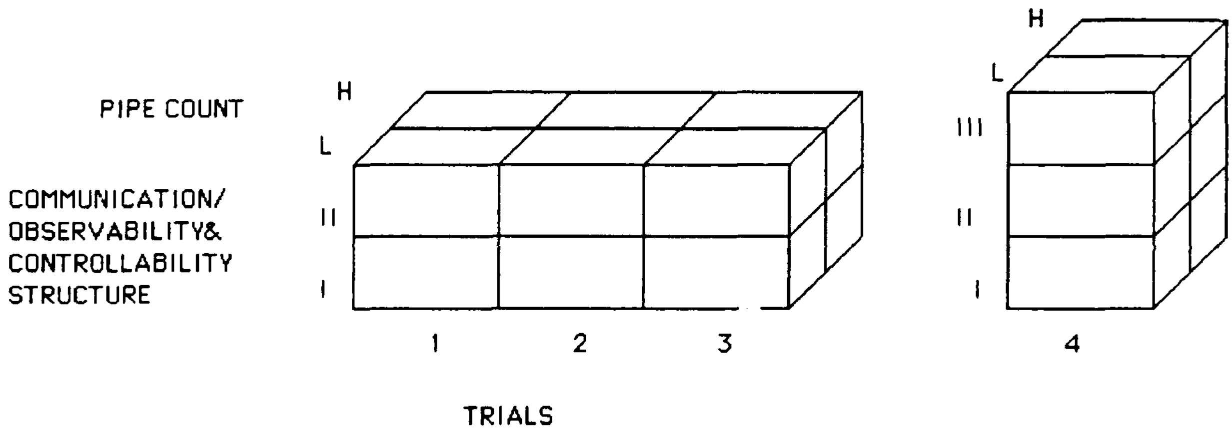


Figure 11. Design Overview

used with repeated trials.

The operators' actions were recorded, and skill acquisition was assessed for a total of four trial units: three trials per group (the acquisition of skills trials) across two levels of pipe/pump count and two communication structures, one trial (the adaptability trial) across two levels of pipe/pump count, two communication structures, and two observability/controllability structures. Each operator's messages sent to other members of the network were recorded and the individual aquisition (subject stations A, B, and C) along with group acquisition of situation assessment skills and performance feedback skills under various forms of partitioning and complexity were assessed. The process control states and control inputs were recorded to assess individual and group performance results for controlling the process states as directed by the experimenters.

3.O SUMMARY OF RESULTS

The subjects' responses to a post-trial survey, administered after each trial showed that the groups trained with low pipe/pump counts perceived their workloads higher than the groups that trained with high pipe/pump counts. Individuals at subject station B, the "hub," for the chain communication groups (structure II) showed much higher ratings than stations A and C and this difference was accentuated when taken to the fourth trial that administered a redistributed set of observables and controllables with the chain communication structure (structure III). This survey showed that the perceived task difficulty means for individuals at subject station A decreased with repeated trails, but, at subject station B the ratings increased with repeated trials. For all groups, those administered structure III gave a lower mean task difficulty rating than those administered their opposite communication structure. This result could probably be accounted for by the newness of the observability and controllability structure and the accompanying skill transfer aspects. The mean time pressure ratings appear to have bottomed-out by the second trial for the groups that trained with the circle communication structure (structure I) and the low pipe/pump count scenarios and chain (structure II) with high pipe/pump count scenarios, yet appear to peak for the circle groups with high pipe/pump counts and chain with low pipe/pump counts. This result could be accounted for by the continued higher level of task loading to which the latter groups were subjected.

Mental and sensory effort ratings grew with repeated trials for the circle groups, but peaked at the second trial for the chain groups. Individuals at subject station B of the chain groups logged less mean frustration than A or C of those groups; subject B of the circle groups was more frustrated than A or C of those groups. For the fourth trial, this continued for chains given structure III, and for circles given either structure II or III. Groups that trained with the chain structure and then administered the circle structure for the fourth trial showed that individuals at subject station B had very high frustration levels compared to A or C of those groups. For all groups, fatigue grew with trials. The perceived performance was higher for the low pipe/pump count groups than the high pipe/pump count groups. Individuals at subject station B of the chain groups gave the highest perceived performance ratings of the chain groups. As trials were repeated, the perceived performance increased markedly for the chain groups. This trend of the chain groups continued for the fourth trial when a circle communication structure was imposed on them. By separating training groups by those that had either high or low pipe/pump count scenarios, it was seen that those that had the low pipe/pump scenarios felt they had done better than those that had the high pipe/pump count scenarios when given a scenario variation (structure III or the communication structure opposite) for the fourth trial.

The actual performance index for each trial, for each group, was recorded as a function of simulation time. As illustrated in Figures 12 and 13 these functions showed that for the first three trials, both the first derivatives of the functions are decreased with time and the overall function decreased with trials. For the first three trials, the mean of the final time performance index, $PI(t_f)$, was lower (better) for the low pipe count groups when compared with the high pipe count groups. This result is shown in Figures 14 and 15. For the first three trials, the chain groups had lower mean $PI(t_f)$ than the circle groups. The chain groups showed a marked decline in the $PI(t_f)$ with trials compared with the circle groups. Those groups that trained with low pipe counts started with low mean values compared to the those trained with high pipe counts for the first trial and their $PI(t_f)$ value continued to decline with trials. Those groups that trained with high pipe counts started with high mean values compared to the those trained with low pipe counts for the first trial

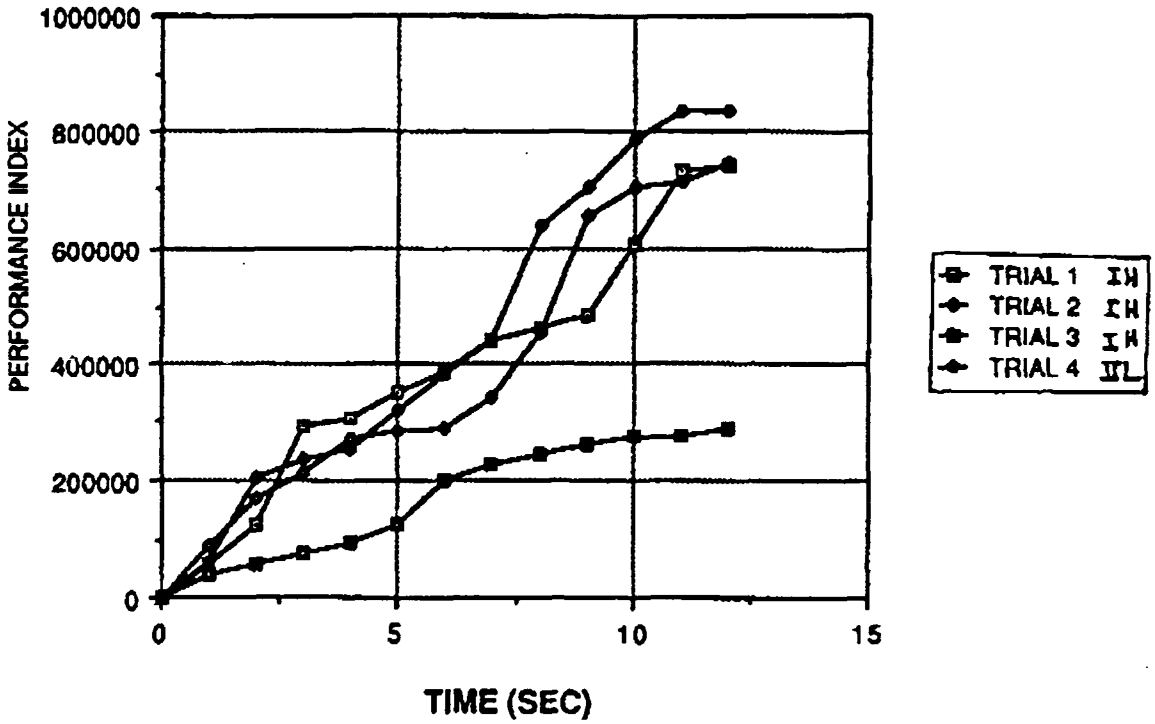


Figure 12. Group 6: Performance Index as a Function of Time, Four Trials

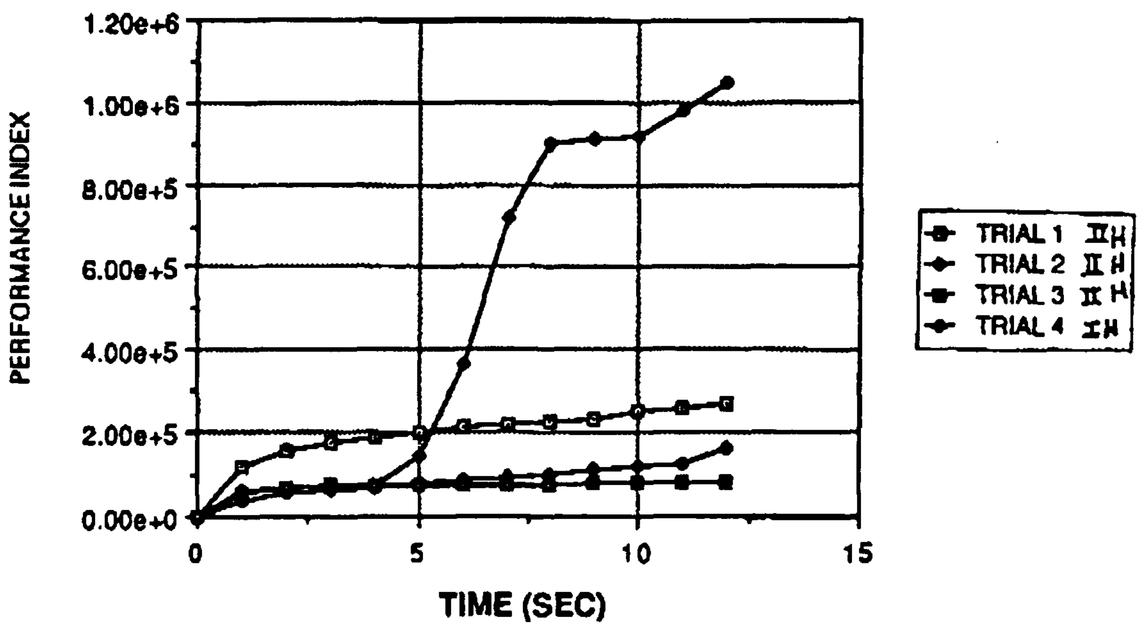


Figure 13. Group 11: Performance Index as a Function of Time, Four Trails

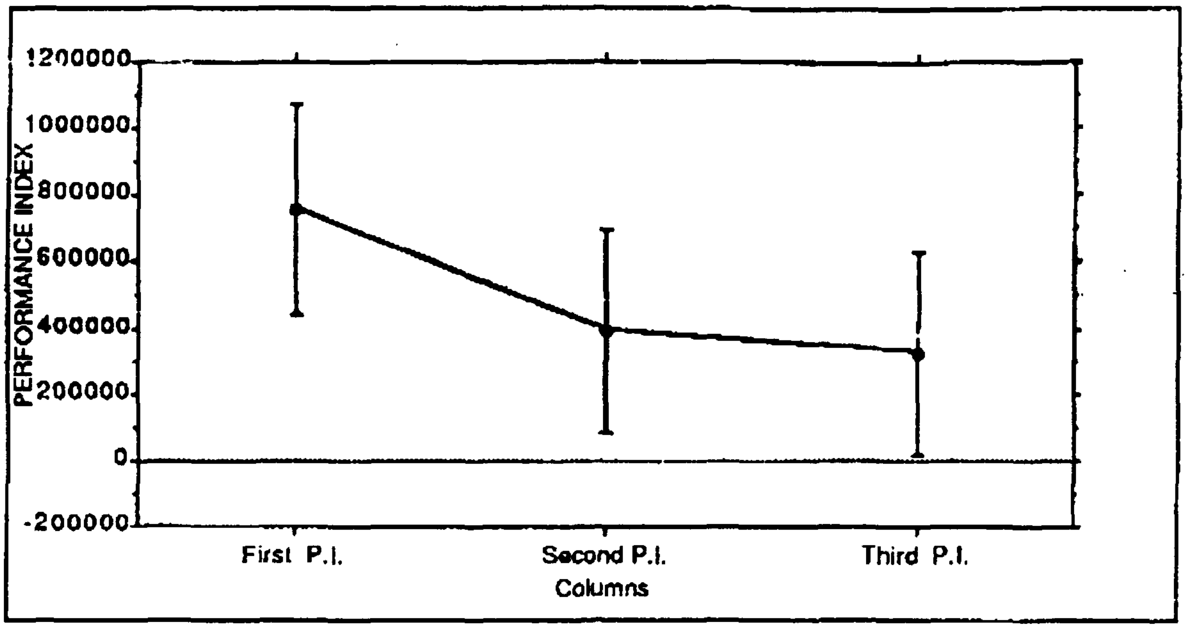


Figure 14. Means and One Standard Deviation Bars for the High Pipe Count Groups for each Trial (1st, 2nd, and 3rd) of the Final Time Performance Index

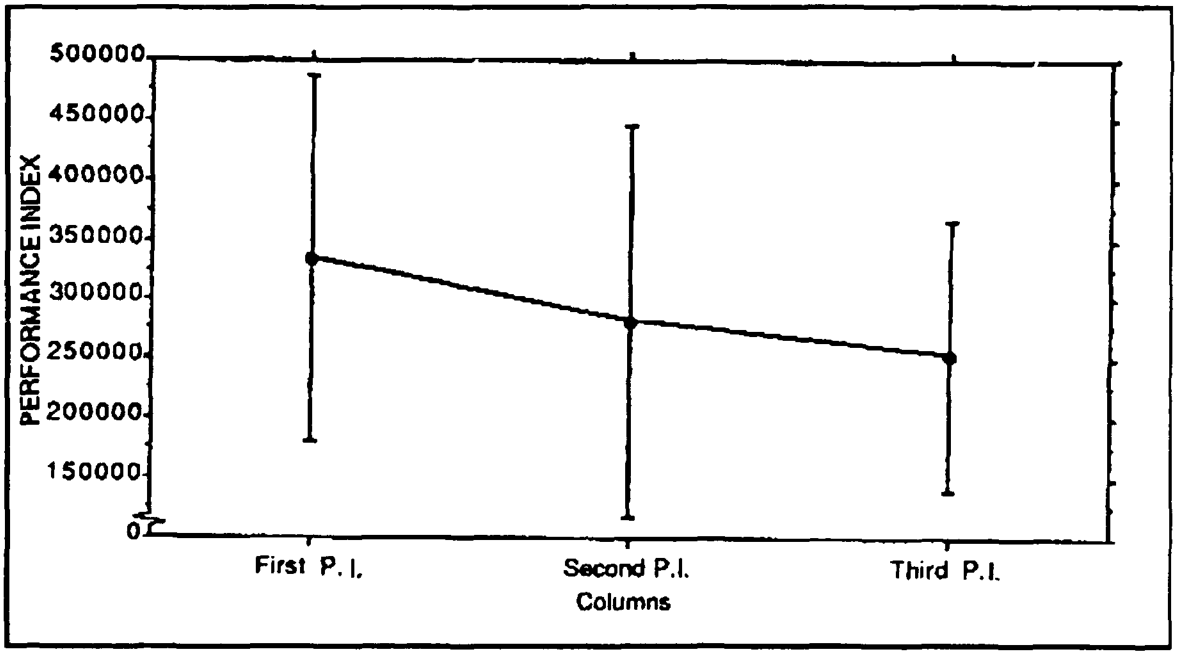


Figure 15. Means and One Standard Deviation Bars for the Low Pipe Count Groups for each Trial (1st, 2nd, and 3rd) of the Final Time Performance Index

and their $PI(t_f)$ means continued to decline with trials but not as low as the low pipe count groups. For the fourth trial, those given the opposite communication structure did better (lower $PI(t_f)$) than those given structure III. Thus, the observability/controllability re-partitioning had a profound effect. The chain groups did better when given the chain communication structure for their fourth trial than the circle groups when given the circle communication structure.

The communication activity was recorded as both a frequency count and a serial connectivity (communication transition matrix) between message types for each subject for each trial. For the first three trials, the communication transition matrices become more dense, on average, with each trial. For those trained with circle groups, the S(uggestion) message classification was the strongest way in which an individual could assert himself or herself to the point of evolving into a leadership role (see Table 1). Those individuals at subject station B who trained with circle groups and had many "suggestions" in turn had many "orders" in the

(IL) SubA1	(IL) SubA2	(H) SubA3	(IL) SubA4
1	1	2	4
1 0 0 1	1 0 0 1	0 0 0 1	0 0 0 0
0 0 0 0	0 0 0 0	1 0 0 0	0 0 0 0
0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0
1 0 0 0	1 0 0 0	1 0 0 0	0 0 0 0

SubB1	SubB2	SubB3	SubB4
3	0	3	3
0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0
0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0
0 0 0 0	0 0 0 0	1 0 1 0	0 0 1 0
0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0

SubC1	SubC2	SubC3	SubC4
3	3	3	3
0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 1
0 0 0 0	0 0 1 0	0 1 1 0	0 0 0 0
0 0 0 1	0 0 1 2	0 1 0 1	0 0 0 2
0 0 0 0	0 1 0 1	0 0 0 2	1 0 1 2

Table 1. Group 1: Communication Action Transition Matrices

fourth trial. Some individuals of the circle groups at subject station C that may have been evolving into a leadership role were not allowed to have an O(rder) classification when administered a structure III scenario for a fourth trial. As illustrated in Tables 2 and 3 and in Figures 16 and 17, the circle groups communicated less frequently than the chain groups. It is noted that Bavelas achieved the opposite

	Pipe Count:	Low	High	Totals:
Communi...	Circle	27 2.556	27 4.519	54 3.537
Communi...	Chain	27 6.296	27 6.815	54 6.556
Totals:		54 4.426	54 5.667	108 5.046

Table 2. The Communication Structure---Pipe/Pump Count (AB) Incidence Table for the Message Frequency

	Subject:	A	B	C	Totals:
Communi...	Circle	18 2.444	18 2.389	18 5.778	54 3.537
Communi...	Chain	18 4.944	18 9.444	18 5.278	54 6.556
Totals:		36 3.694	36 5.917	36 5.528	108 5.046

Table 3. The Communication Structure---Subject Station (AC) Incidence Table for the Message Frequency

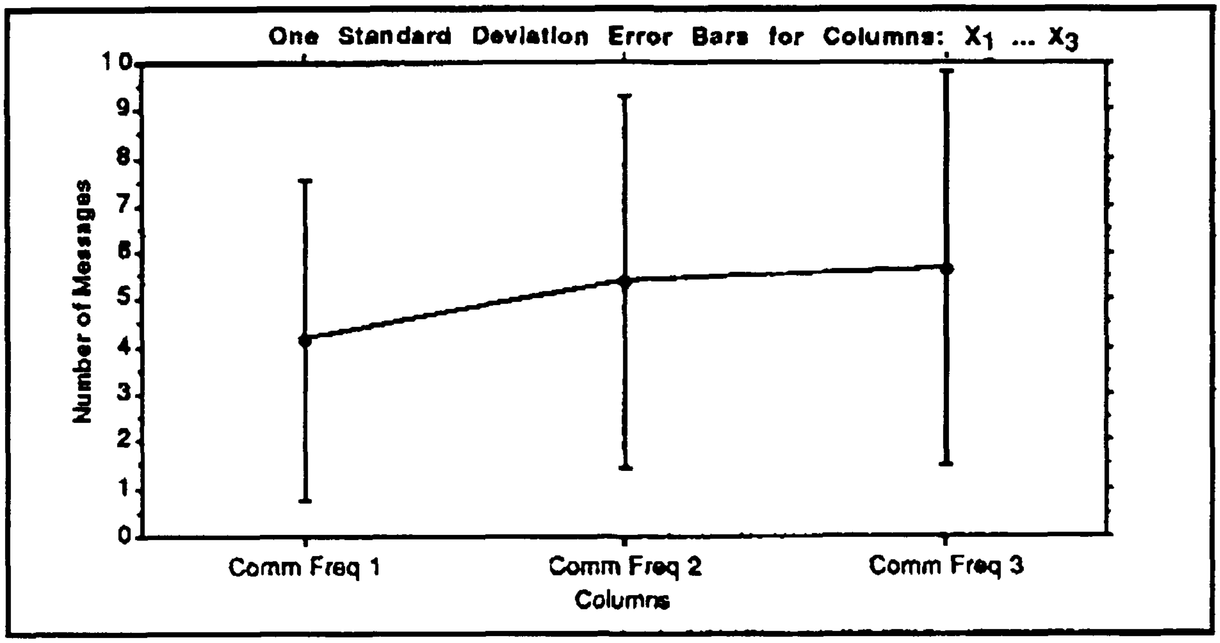


Figure 16. Message Frequency Means and One Standard Deviation bars for all Groups for all Subjects for Each Trial (1st, 2n, 3rd)

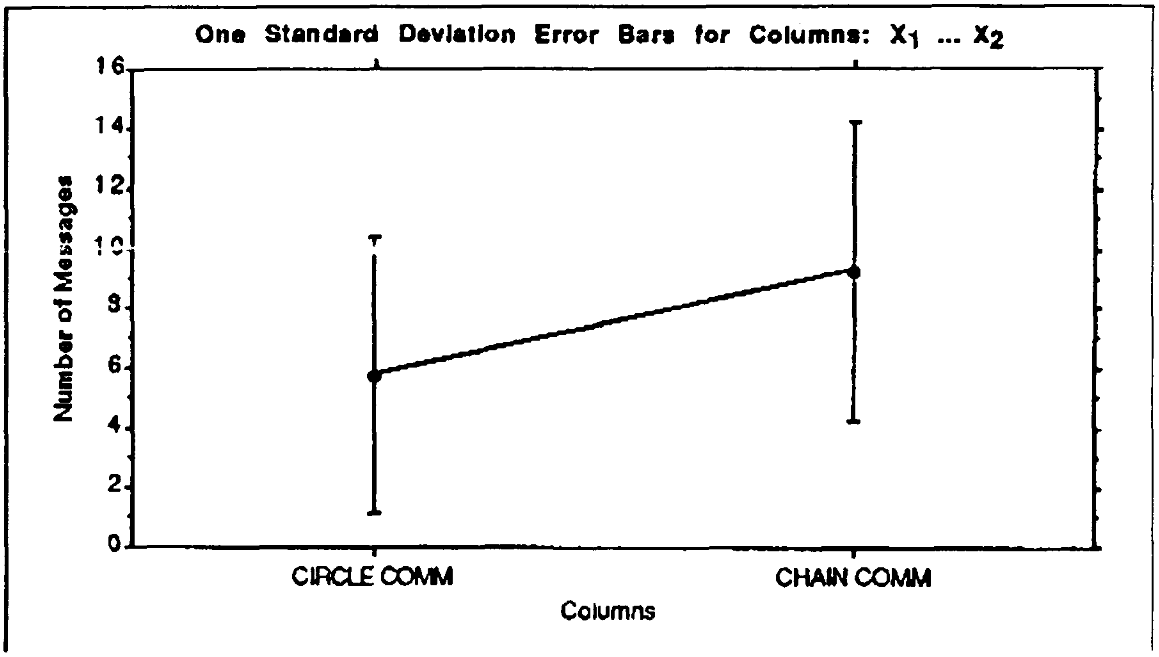


Figure 17. Message Frequency Means and One Standard Deviation bars for the Fourth Trial per Subject

result in static scenario studies. The individuals at subject station B for the chain groups, on average, communicated twice as frequently as the other two chain group member mean values. The mean message frequency for the groups trained with the circle communication structure was much less than the groups trained with the chain structure when administered a variation for the fourth trial. Both groups communicated more, on average, when administered structure III than when administered their opposite communication structure. This could be accounted for by the newness of the fourth trial structure.

The control (pipe/pump flow change) activity was recorded as both frequency count and serial connectivity between pipes changed for each subject for each trial. The serial connectivity was recorded in subject submatrices, except for structure III, where subject C had a full matrix description. For the first three trials, the action transition blocks become more dense, on average, with each trial. Only the circle groups with low pipe scenarios showed blocks getting less dense (sparser) by the third trial (see Table 4). The pipe flow change frequency means of all other groups increased with trials. For the fourth trial, the groups that trained

(IL) 9 SubA1

0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	2	0	3
0	1	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	4	0	0	1

(IL) 8 SubA2

0	0	0	0	0	0	0	0	0
0	2	0	0	0	0	1	0	3
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	2
0	1	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0
0	2	0	0	0	4	1	0	0

(IL) 9 SubA3

0	0	0	0	0	0	0	0	0
0	2	0	0	0	2	0	0	1
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	2	0	0	2
0	0	0	1	0	1	1	0	0
0	0	0	0	0	0	0	0	0
0	3	0	0	0	0	1	0	2

(IL) 7 SubA4

1	2	0	0	0	1	0	0	0
2	1	1	0	1	0	0	0	0
0	1	0	0	0	0	0	0	1
0	0	0	0	0	1	0	0	0
0	0	0	0	1	0	2	0	0
1	0	0	1	0	1	0	0	1
1	1	1	0	1	0	0	1	0
0	0	0	0	0	1	0	1	1
0	0	0	0	0	0	2	1	2

16 SubB1

0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	1	1	0
0	0	0	0	0	0	1	0	0
0	0	0	1	0	0	2	0	0
0	0	0	1	0	0	1	2	0
0	0	0	0	0	0	0	0	0
0	1	1	0	1	0	1	3	0
0	2	0	1	1	0	0	3	0
0	0	0	0	0	0	0	0	0

76 SubB2

0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	3	0	0
0	0	0	0	0	0	2	1	0
0	0	0	0	0	0	0	0	0
0	0	0	3	3	0	0	2	0
0	0	0	0	0	0	2	2	0
0	0	0	0	0	0	0	0	0

13 SubB3

0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	2	1	0
0	0	0	0	0	0	0	0	0
0	0	0	0	2	0	4	3	0
0	0	0	0	1	0	2	0	0
0	0	0	0	0	0	0	0	0

16 SubB4

0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	2
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	3
0	0	0	0	0	0	0	6	2
0	0	0	0	3	0	1	3	7

26 SubC1

1	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0
0	0	0	0	1	1	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	2
0	0	0	0	0	0	0	2	1
0	0	0	0	0	0	0	0	0
1	0	1	0	0	1	0	2	3
1	0	1	0	2	1	0	3	4

27 SubC2

0	0	1	0	1	1	0	0	1
0	0	0	0	0	0	0	0	0
2	0	0	0	0	1	0	1	0
0	0	0	0	0	0	0	0	0
0	0	1	0	0	1	0	0	1
0	0	0	0	2	1	0	0	1
0	0	0	0	0	0	0	0	0
1	0	1	0	0	0	0	0	0
1	0	1	0	0	0	0	2	4

27 SubC3

1	0	1	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	2	0	1	0
0	0	0	0	0	0	0	0	0
1	0	0	0	0	1	0	r	0
0	0	1	0	1	0	0	1	3
0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	1	1
1	0	1	0	1	1	0	0	3

27 SubC4

0	0	0	0	0	0	1	1	0
0	0	0	0	0	0	0	0	1
0	0	0	0	0	1	0	0	2
1	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	2
1	0	0	0	0	0	0	1	0
0	0	0	0	0	0	1	0	1
0	0	3	2	0	2	0	0	2

Table 4. Group 1: Action Transition Matrices

with the circle communication structure (I) were administered a chain communication structure (II) and their control activity, on average, was at the same mean as the peak of the second trial. For the fourth trial, the groups that trained with the chain communication structure (II) were administered a circle communication structure (I) and their control activity, on average, was below the means of the first three trials. For all groups administered structure III, their mean control activity was much less than in any of their first three trials. The reasons for this significant drop included both added group loading for reorientation and a through-put constraint because only subject C could make pipe/pump flow changes. When administered structure III for the fourth trial, those groups that trained with structure I showed less activity than those groups that trained with structure II. The reason for this difference appears to be that structures II and III share obvious communication structures. A short term control strategy was defined as changing only pipes directly connected to sinks. A long term strategy was defined as being beyond short term strategies since they included over and underflow concerns in achieving a well regulated steady-state flow. From a review of the action transition block, it appeared that the circle groups tended to evolve from short term strategies of regulation to long term strategies by trial 3, while chain groups tended to stay with short term strategies for every trial. But, for some of the reasons pointed out by Moray, et al, 1986, the communication and pipe flow change action transition matrices showed great individual variations in behavior.

4.0 DISCUSSION AND CONCLUSIONS

The design of this problem-solving situation was intended to provide a "testbed" approach such that information gained from these experiments might be applied to such diverse areas as the optimal allocation of raw material and man/ machine power (or energy) in a hierarchal, manufacturing environment or to the optimal assignment of troops and equipment in a battlefield environment.

By synthesizing major research results of others in these areas and extending the investigation to networks and hierarchies, our data have suggested that for this abstract, yet tangible, dynamic scenario, chain, or linearly connected, groups obtain control skills faster and communicate more frequently when compared against circle, or star, groups. An increase in pipe selection options for control input paths, intended to increase system flexibility for achieving group optimal transient and steady-state control, actually appeared to cause a decrease in performance. We believe the evidence suggests this result was related to overburdening the subjects' decision information processing capability.

The summary of the major findings of this research are: 1) chain groups reached their respective "steady-state" final time performance values in fewer trials; 2) circle groups had sparser communication transition matrices; 3) chain groups tended to focus on short term control strategies; 4) too much of an increase in the number of available control input path options will decrease group performance by overloading the operators even though this increase permitted more potential regulation solution sets ; and 5) the very communicative individuals in the "hub" of the chain groups rate their group performances higher and the "negative" topics lower than the other two group members.

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